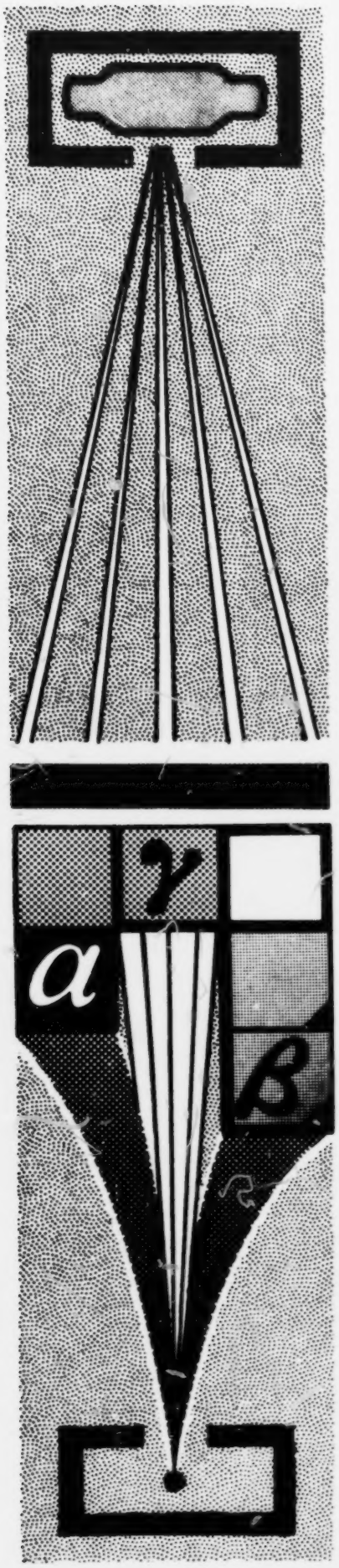

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X-RAY FLUOROSCOPIC SCREENS - HISTORY, CRYSTAL KINETICS, PRELIMINARY REPORT on "AGING"

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service

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This is a preliminary report on a long-range study of the factors which reduce the light output of fluoroscopic screens. New screens are being exposed to x-rays, sunlight, incandescent lamps and fluorescent lamps. The light output of these screens is measured monthly. Comparative measurements are also being made on older screens. These measurements indicate that the new phosphors and technological advances over a 40-year period have enabled a decrease in patient exposure by a factor of eight to ten.

Based on the study results, it is recommended that all flucroscopic screens made before 1947 should be replaced with screens incorporating the new phosphors and technological advances.

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X-RAY FLUOROSCOPIC SCREENS - HISTORY, CRYSTAL KINETICS, PRELIMINARY REPORT on "AGING"

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We are indebted to Mr. John P. Kelley and Mr. Kenneth E. Weaver for continuing the study, and to Mr. Neil Jordan who took the data on light transmission through lead glass.

FOREWORD

The Bureau of Radiological Health implements a national program designed to reduce the exposure of man to hazardous ionizing and nonionizing radiation.

Within the Bureau, the Division of Medical Radiation Exposure deals with 1) the reduction of unproductive ionizing radiation exposure of patients, workers, and others exposed by the use of x-rays and other machine-produced ionizing radiation, radioactive materials and radiopharmaceuticals, and 2) the improvement of radiological "systems" and methodology in the healing arts.

The Bureau publishes its findings in appropriate scientific journals and technical report series for the Bureau's divisions, offices, and laboratory.

The technical reports of the Division of Medical Radiation Exposure allow comprehensive and rapid publishing of the results of intramural and contractor projects. The reports are distributed to State and local radiological health program personnel, Bureau technical staff, Bureau advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press, and other interested individuals. These reports are also included in the collections of the Library of Congress and the National Technical Information Service.

I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

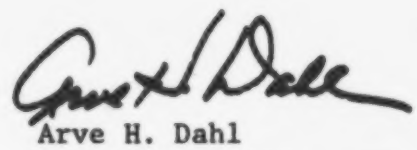
John C. Villforth
Director
Bureau of Radiological Health

PREFACE

This report describes a long-range study of the factors which reduce the light output of fluoroscopic screens. New screens are being exposed to x-rays, sunlight, light from incandescent lamps, and light from fluorescent lamps. Light output of the screens is measured monthly. Comparative measurements are also being made on older screens. Data presented indicate that the new types of phosphors and technological advances over a 40-year period have made it possible to decrease patient exposure by a factor of eight to ten. Based on the study results, it is recommended that all fluoroscopic screens made before 1947 should be replaced with screens incorporating the new phosphors and technological advances.

Also contained herein are a brief history of the development and use of x-ray fluoroscopic screens, an exposition of the luminescent process in inorganic crystals, and a brief summary of some previous reports of fluorescent screen deterioration.

The study is being performed at the X-Ray Science and Engineering Laboratory of the Oregon State University and has received support from the U.S. Public Health Service through Contract No. PH 86-65-92 and Grant No. 5T1RH55-05(67).



Arve H. Dahl
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Division of Medical Radiation
Exposure

CONTENTS

		Page
FOREWORD		iii
PREFACE		v
I.	INTRODUCTION	1
II.	HISTORICAL DEVELOPMENT OF X-RAY FLUORESCENT SCREENS	1
III.	THE LUMINESCENT PROCESS IN INORGANIC CRYSTALS	7
IV.	FLUORESCENT DETERIORATION REPORTED	16
V.	X-RAY APPARATUS AND INSTRUMENTATION	20
VI.	EXPOSURE CONDITIONS AND LUMINESCENT RESPONSE	28
VII.	LUMINESCENT RESPONSE	34
VIII.	EXPERIMENTAL DATA	34
IX.	SUMMARY AND CONCLUSIONS	45
REFERENCES		47

FIGURES

1. Energy-band diagram for luminescent inorganic crystal. 8
2. Photoconducting crystal. 10
3. Effect of different activator atoms in zinc sulfide crystal matrix 14
4. Spectral distribution of energy and relative visibility for (1) ZnS:Ag, (2) Zn(50%)-Cd(50%)S:Ag, and (3) Zn(20%)-Cd (80%)S:Ag. 15
5. Special X-ray unit with "Brightness Spot Meter" mounted on adapter. 21
6. Special X-ray unit with front panels open and screen exposure holder intercepting the beam 22
7. Geometry of special X-ray setup. 23
8. Table top exposure rate versus tube current for special X-ray unit 25
9. Screen exposure rate versus tube current with 3 sheets of 1/2-inch-thick Mix-D in the beam 26

FIGURES (continued)

Page

10. Comparison of C.I.E. luminosity curve and spectra "Brightness Spot Meter" sensitivity. 27
10A. Percent transmission of light through 6.35-millimeter-thick lead glass 30
11. Typical light spectra from solar irradiation at sea level, tungsten lamp and daylight-type fluorescent lamp 32
12. Foot-lamberts versus exposure rate for Group I and Group II fluoroscopic screens at 100 kVp and 70 kVp 35
13A. Relative luminescent response of screens exposed to light from fluorescent lamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure. 37
13B. Relative luminescent response of screens exposed to light from fluorescent lamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure. 38
14A. Relative luminescent response of screens exposed to light from tungsten lamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure. 39
14B. Relative luminescent response of screens exposed to light from tungsten lamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure. 40
15. Relative luminescent response of screens exposed to X-rays, excited by 0.5 R/min. at 100 kVp versus the number of weeks or days of exposure. 41
16A. Relative luminescent response of screens exposed to sunlight, excited by 0.5 R/min. at 100 kVp versus the number of hours of sunlight or days of exposure. 42
16B. Relative luminescent response of screens exposed to light from sunlamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure 43

TABLES

1. Division of fluoroscopic screen test population. 29
2. Ultraviolet transmission factors for nominal 6.35 mm lead glass. 29
3. Luminescent response of a number of new and old fluoroscopic screens. 44

I. INTRODUCTION

From the time when fluoroscopic screens were first used there have been scattered references to reduction in their light output due to age, use, etc. References are scarce and usually devoid of quantitative data. A long-range program has been set up in an effort to arrive at some meaningful information.

A group of 24 fluoroscopic screens are being used in this study, 12 each from two manufacturers. All screens were of the zinc-cadmium sulfide phosphor type mounted on plastic backing material. The screens were divided into test groups and are being exposed to X-ray, sunlight, light from incandescent lamps and light from fluorescent lamps. Test conditions were so designed that they could be related to some realistic exposure to which the screen in a diagnostic unit might be subjected.

To determine their relative condition, measurements of the light output of all the screens are taken at monthly intervals. These measurements are made under controlled conditions utilizing a specially-constructed X-ray unit and a direct-reading light meter employing a photomultiplier tube as the detector. By use of a direct-reading instrument, calibrated in footlamberts, measurements are made independently of the sensitivity of the observer's eye and require no time-consuming matching of brightness. Calibration of the light meter is maintained by means of a regulated brightness source.

In addition to the new screens, a number of old screens have been obtained and measurements taken to compare them with current screens.

Before starting to take data, it was decided to learn as much as possible about the history, chemistry, solid-state effects and other related factors pertaining to inorganic phosphors. This information is already available, of course, but the references are scattered through the literature and our aim has been to bring it into a single reference.

II. HISTORICAL DEVELOPMENT OF X-RAY FLUORESCENT SCREENS

The first detailed study of fluorescence was made by Sir George Gabriel Stokes (32,33,34,35). According to his obituary notice, carried in the Proceedings of the Royal Society, Lord Rayleigh (30) states that Stokes' work on what is now called fluorescence was the most far reaching of his experimental discoveries.

Various reports of the phenomenon now known as fluorescence can be found in the literature well before the investigations of Stokes (8). In 1575 Nicolo Monardes reported that a solution prepared from the extract

of a Spanish wood, a solution used as a treatment for kidney disease, appeared bluish when exposed to sunlight. The blue color taken on by this yellow solution was also reported by Sir Isaac Newton. Neither understood the significance of their observation. In 1833 Sir David Brewster reported that an alcohol solution of chlorophyll prepared from green plant leaves showed a bright light of a blood red color when exposed to light contrasting with the green color of the solution (32). Brewster's explanation was that an internal dispersion of some unknown substance was responsible for the observed red color.

Sir John Herschel discovered that a weak solution of quinine sulfate, which appeared transparent and colorless when viewed by transmitted light, exhibited a peculiar blue hue in a portion of the fluid when exposed to the incident light (33). Herschel observed that when the fluid was illuminated by a beam of ordinary daylight, the blue hue was produced in only a very thin stratum of the solution adjacent to the incident light beam. His investigations showed that the blue light produced was unpolarized, and the transmitted beam was incapable of producing the effect in a second container of the quinine solution. A beam of light modified in such a manner was termed "epipolized" by Herschel. Brewster found some of Herschel's observations difficult to explain, in particular, that the whole or a great portion of the dispersed beam was unpolarized, whereas a beam reflected from suspended particles might be expected to be polarized by reflection. From the general identity attending the two phenomena, Brewster was led to conclude that "epipoly" was merely a particular case of internal dispersion.

Stokes had been working with polarized light from various sources and became interested in the observations of Brewster and Herschel. Stokes found many of their explanations difficult to accept. In particular, what rays were capable of producing the blue hue in a quinine solution and why their capability was so quickly extinguished resulting in the production of only a thin stratum at the interface of the incident light beam and the solution. After considerable experimentation, Stokes was able to show that the process is not due to internal dispersion of suspended particles, but is instead similar to phosphorescence. He suggested the term fluorescence be used to describe the phenomenon (34).

> "In my former paper I suggested the term fluorescence, to denote the general appearance of a solution of sulfate of quinine and similar media. I have been encouraged to give this expression wider signification, and henceforth instead of true internal dispersion, I intend to use the term fluorescence which is a singular word not implying the adoption of any theory."

Stokes also worked with a number of other fluorescent materials. Of particular significance were the platinocyanides of calcium, barium and strontium which he reported to fluoresce in different shades of green (34) when exposed to visible light.

Lenard, while working with gas discharge tubes, was the first to discover that it was possible to produce luminescence in fluorescent materials outside a Crookes tube. Roentgen's discovery of X-rays was really an extension of Lenard's work. Roentgen discovered that, in fact, some visually undetectable type of radiation was produced in the discharge of a Hittorf or Crookes tube. This invisible radiation was able to penetrate optically-opaque material and excite certain fluorescent materials.

The fluorescent screen that Roentgen used in making his discovery consisted of barium platinocyanide crystals deposited on a cardboard backing. This type of fluorescent crystal had been studied by Stokes and subsequently used by many experimenters of that time in their investigations of the gas discharge phenomenon. These barium platinocyanide screens were very unstable. They were prepared by precipitation from an aqueous solution onto some backing material such as cardboard to give structural support. Screens prepared in this way contained loosely-bound water of hydration, which in turn was responsible for the crystals ability to fluoresce. These screens were very expensive and subject to deterioration. The water of hydration contained in the crystal was easily lost under the influence of heat and dry atmospheric conditions. As previously mentioned, the loss of this water would render the crystal nonfluorescent. Although having many drawbacks, barium platinocyanide screens were used exclusively for a number of years in fluoroscopic screens because their yellow-green fluorescence closely matched the visual response of the eye.

The great interest generated by Roentgen's discovery of X-rays renewed the study of the fluorescent process and the search for new and better fluorescent crystals. One of the first to take up this study of fluorescence was Thomas A. Edison. From January to March of 1896 he investigated more than 8,000 different materials. His basic interest had been in trying to develop a new electric lamp. Edison found more than 1,800 different materials would fluoresce to some degree, but found calcium tungstate to be the best. He found this material to be much superior to barium platinocyanide; it was relatively stable and had a light output about six times greater.

Edison's practical nature and creative mind led him to try to devise a light source using fluorescent materials. He reported in Century Magazine of 1896 (5)

> "When the X-ray came up, I made the first fluoroscope using tungstate of calcium. I also found that this tungstate could be put into a vacuum chamber of glass and fused to the inner walls of the chamber; and if the X-ray electrodes were let into the glass chamber and a proper vacuum was attained, you could get a fluorescent lamp of several candle power. I started in to

> make a number of these lamps, but I soon found that the X-rays had affected poisonously my assistant, Mr. Dally, so that his hair came out and his flesh commenced to ulcerate. I then concluded it would not do, and that it would not be a very popular kind of light; so I dropped it."

Edison's fluoroscope consisted of a box, curved at one end to fit closely over the forehead and eyes; at the other end a thin layer of calcium tungstate was spread on a stiff backing material. By placing the object to be viewed between the X-ray tube and the fluorescent screen a shadow image could be observed. This apparatus was first shown to the public at the Electrical Exhibition of 1896 held at the Grand Central Palace in New York City. The fluoroscope was demonstrated as part of Edison's exhibit and was set up so the public could view their own bones.

Edison prepared his crystal calcium tungstate by fusing together anhydrous sodium tungstate and calcium chloride. This mixture was then spread on a backing material using collodion as a binder. The firm of Aylsworth and Jackson; located in Orange, New Jersey, manufactured these screens on a commercial basis for Edison. These screens were reported to have considerable fluorescent lag and would deteriorate rapidly (6), but they were an improvement over barium platinocyanide and were thus considered very satisfactory for the times.

Spectral studies have shown that calcium tungstate fluorescence lies predominantly in the blue-violet region of the spectrum. This characteristic has precluded its use as a fluoroscopic screen since the eye's response to this portion of the spectrum is low. Its spectral response corresponds quite closely to that of a photographic emulsion and calcium tungstate is the predominant phosphor used for X-ray intensifying screens.

In the early days the Germans were quite active in the manufacture of screens. One of the screens made by them was "Astral Fluorescent Screens" produced through the use of willemite, a natural zinc silicate. Natural zinc silicate was quite scarce and artificially-produced crystals were soon used in the production of these screens. Zinc silicate was not entirely satisfactory; its yellow-green fluorescence did not closely match the optimum film response spectrum and also displayed extreme lag. Another German firm produced an intensifying screen known as a "Gehler Folie" from Scheelite, a natural calcium tungstate. These screens were exported to the United States in large numbers prior to the First World War.

When it became difficult to obtain screens from the European manufacturers, a number of United States products became available. In 1912 Dr. Herbert Threlkeld Edwards produced a screen of calcium tungstate which was reported to be relatively fast and of good quality. A year later the Snook-Roentgen Manufacturing Company introduced the Snook "Lagless Intensifying Screen." This screen, developed by Carl V. S. Patterson, then working for the Snook concern, was similar to the Threlkeld Edwards screen.

Patterson, who had left Snook to form his own company, introduced an improved calcium tungstate screen in 1916. This screen had a much finer grain and showed very little lag. In 1918, Patterson also developed the double-screen technique to be used with the new duplitized film having an emulsion on both sides of the base.

The development of the modern fluoroscopic screen proceeded somewhat independently of the intensifying screen due to different design criteria. As pointed out by Levy and West (17), a screen that is to be used for visual examination must exhibit certain characteristics:

A. "The intensity of illumination of the fluorescent screen, when excited by X-rays, should be as great as possible."

The visual impression of brightness is dependent on the spectral content of the excited fluorescence. To be most efficient, this excited fluorescence should correspond to the spectral sensitivity of the human eye. The maximum response of the human eye corresponds to a wave length of about 5,550 Angstroms. The yellow-green fluorescence of barium platinocyanide lies in this region of maximum spectral sensitivity. Its sensitivity was one reason for its utilization as a phosphor in fluoroscopic screens until 1914 when Patterson introduced the "Type A" cadmium tungstate screen for fluoroscopy.

B. "The definition, which can be described as the screen's ability to show fine detail without blur, should be high."

To obtain this fine detail, the fluorescent crystals must be deposited in a thin layer.

C. "The screen should show very little afterglow or lag since a faint trace of the previous image on the screen will lead to confused and blurred results."

Before Levy and West (18) developed a method of producing a zinc sulfide phosphor with little afterglow, this characteristic of zinc sulfide prevented its use as a fluorescent crystal in fluoroscopic screens. An interesting development prior to Levy and West's work was reported by I. Seth Hirsch (11) in which he specifically utilized the inherent afterglow of a fluoroscopic screen in a device capable of image storage. In Hirsch's apparatus, a screen with extreme lag was used on which an image could be stored for subsequent examination. The screen was so constructed that it could be heated with an electrical element at some time after the exposure. Heating would cause the thermal release of a large number of electrons from their trapping centres with the subsequent production of a bright, visible image.

Except for special applications, the lag of a fluorescent screen is considered an undesirable quality.

D. "The screen should be sensitive to hard radiation."

When X-radiation is incident on matter, the soft, low energy radiation will be attenuated to a greater degree than will the higher energy portion of the spectrum. This effect will cause a shift in the effective energy of the beam to a higher value. In a fluoroscopic examination the patient will act as an attenuator and the spectral distribution of the beam incident on the fluoroscopic screen will be shifted to a higher effective energy. To be most efficient, the fluoroscopic screen should be more sensitive to the higher energy radiation. Zinc silicate is one example of a phosphor whose response decreases with increasing energy.

E. "The screen contrast should be good."

Contrast which can be described as the density difference observable between areas is dependent upon the color of fluorescent emission and the amount of scatter in the screen. Here again, to be most effective the excited fluorescence should as nearly as possible correspond to the spectral sensitivity of the eye.

F. "The screen should be durable and undergo little deterioration."

As previously described, the deterioration of the fluorescent capabilities of barium platinocyanide, as a result of the loss of water of hydration, was an unfavorable characteristic in its use as a phosphor for fluoroscopic screens. But, due to the fact that its spectral response was closely matched to the characteristic sensitivity of the human eye, barium platinocyanide was used predominantly for fluoroscopic screens until 1914. In June of that year, Patterson introduced the first cadmium tungstate screen. This screen, known as a "Type A", was not subject to early deterioration as was barium platinocyanide.

The development of zinc sulfide phosphors by Levy and West (18) caused a change to the use of this type of crystal phosphor in fluoroscopic screens. They were able to develop techniques for producing zinc sulfide with little afterglow. By varying the proportions of other components, they were able to change the spectral response of the phosphor. The final substance arrived at was zinc-cadmium sulfide. The desired characteristics of an ideal fluorescent screen for visual examination, as outlined by Levy and West (18), were most nearly met by this material. Since 1933, this type of crystal phosphor has been the primary material used in fluoroscopic screens.

III. THE LUMINESCENT PROCESS IN INORGANIC CRYSTALS

The basis of an inorganic phosphor is a pure, insulating crystal which is given luminescent properties by the addition of a small number of impurity atoms. These additional atoms occupy interstitial, or substitutional, positions in the crystal matrix lattice.

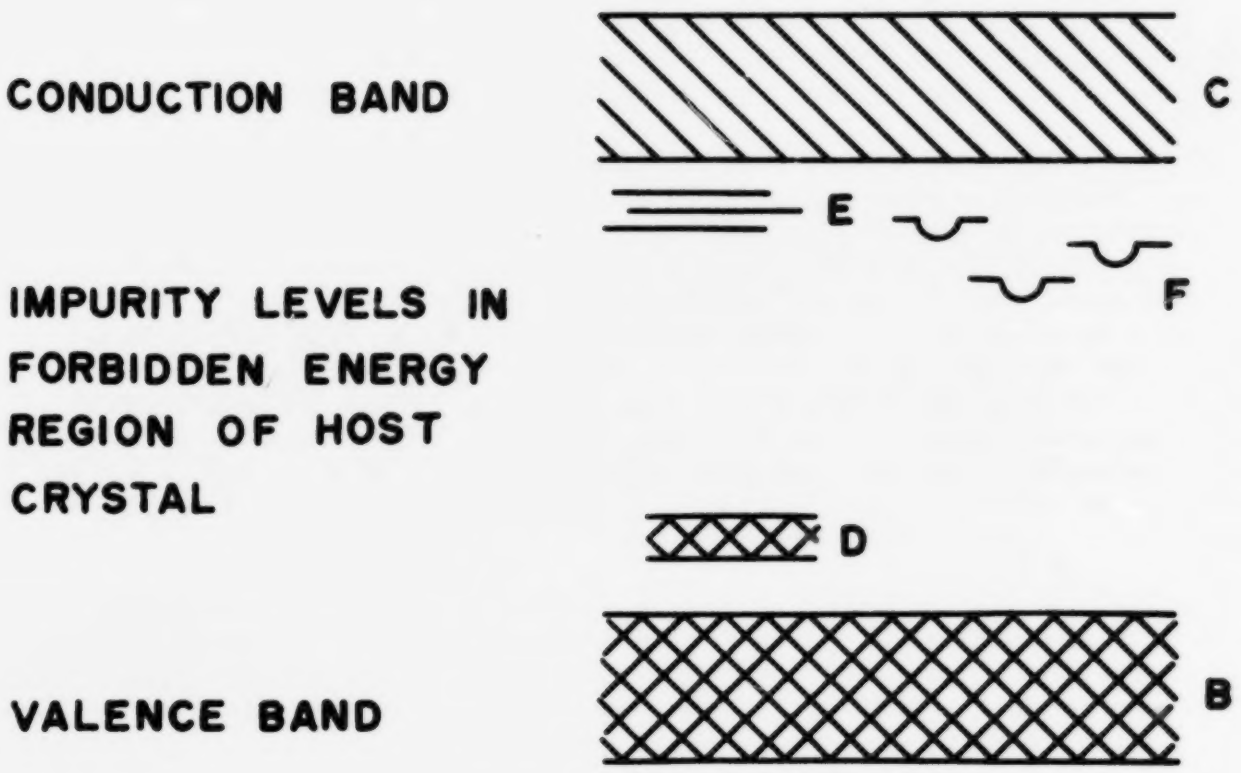
Figure 1 shows an energy-band diagram for a luminescent inorganic crystal. The narrow energy levels which exist in the atom in free space are broadened into bands by the fields due to surrounding ions. These bands in an insulator are filled and, although the electrons in these bands may move freely from ion to ion, the total state of motion cannot be altered by an electrical field and electrical conduction cannot take place. Some distance above the filled valence band there is an empty band, C, corresponding to the state of a freed electron. This is known as the conduction band. If an electron is raised from the valence band to the conduction band, the movement of the electron in C and the positive hole in B can give rise to a current. This phenomenon is known as photoconduction.

Impurity atoms, or lattice irregularities, give rise to localized electron states such as D, E and F with narrow energy levels which may occur in the forbidden region between the conduction and valence band of the host crystal. These positions are known as centres. Electrons moving in the vicinity may occupy these positions.

The centres are of three main types: (1) Luminescent centres in which the transition to the ground state is accompanied by the emission of a photon. For ZnS, Cu or Ag atoms are commonly used to create this type of centre. (2) Quenching centres in which radiationless loss of energy can occur; Fe and Ni are examples of elements that will create quenching centres. (3) Electron traps which have metastable levels from which the electron may return to the conduction band by acquiring thermal energy from the lattice vibrations.

The energy band picture of an ideal crystal cannot account for all the excited states of the solid. It has been shown that besides the excited states in which the free electron and hole are produced, there exists the possibility of lower energy excited states, such as E, for which photoconduction does not take place (16). These states constitute a neutral unit or bound state. These bound electron hole pairs are known as excitons or exciton states; this may correspond to the excited state of an impurity atom or some normally bound excited state.

Photoconducting states are of primary interest for crystals such as ZnS. Excitation raises electrons from the valence band or from the activator centres into the conduction band of the crystal. Between the valence band and the conduction band lie the impurity centres.



B. VALENCE BAND
C. CONDUCTION BAND
D. GROUND ACTIVATOR LEVEL
E. EXCITATION LEVELS
F. TRAPS

Figure 1. Energy-band diagram for luminescent inorganic crystal

The recombination centres for electrons and holes are characterized by an effective cross-section σ_e for electron capture and σ_t for hole capture. A centre is a luminescent centre if the probability of radiative emission P_r is greater than that for non-radiative emission P_{nr}.

$$P_r >> P_{nr}$$

A centre is a quenching centre if the opposite is true. In ZnS:Fe, ZnS:Ni, ZnS:Co the impurities create quenching centres and their introduction into the crystal matrix results in a substantial reduction in luminescence. Elements such as Ag, Cu and Mn are commonly used to produce activation centres. Electron traps and electron donors show a large capture probability for conduction electrons, but transition from them to the valence band is almost forbidden. Electrons residing in traps cannot usually drop to the ground level directly but, instead, must first be given sufficient energy to be raised to the conduction band and subsequently drop to the valence band or activator centre. If the level is normally empty, it constitutes an electron trap; if normally occupied, it is a donor level.

ZnS:Ag and CdS:Ag are both primarily photoconducting crystals (figure 2). According to the description by Curie (4), excitation raises electrons from the valence band or from the luminescent centres into the conduction band of the crystal. Between the valence and conduction bands we have to consider the recombination centres, donor levels and electron traps.

Luminescence can be either fluorescence or phosphorescence. According to the earlier definitions, fluorescence is light emission that does not persist for any considerable length of time following excitation. For example; an often seen value for the limit of this persistence is $\tau < 10^{-8}$ seconds. Under this classification, phosphorescence is luminescence which persisted longer than the selected differentiating time.

A more exact distinction between fluorescence and phosphorescence can be made by reference to the process taking place (27). Under this classification, fluorescence is due to the spontaneous transition of a molecule from its excited state to a lower energy level. The mean life of this process depends only on transition probability; in most cases it is very short, $\tau < 10^{7}$ seconds, but may be delayed up to one second. This process is nearly independent of temperature. The characteristic feature of phosphorescence is that the excited electron does not immediately emit light by returning to the ground state, but passes instead into a metastable or quasistable state known as a trapping centre. This trapping site lies slightly below the excited energy level so that once the electron is trapped, energy must be supplied to remove it from the centre. This energy can usually be gained thermally. Once the electron has been removed from the trap to the excited state, it can then return to the ground state with light emission accompanying this transition, or the electron may be retrapped. Phosphorescence is a temperature-dependent phenomenon and will occur within a short time, if the trap depth is shallow or the temperature

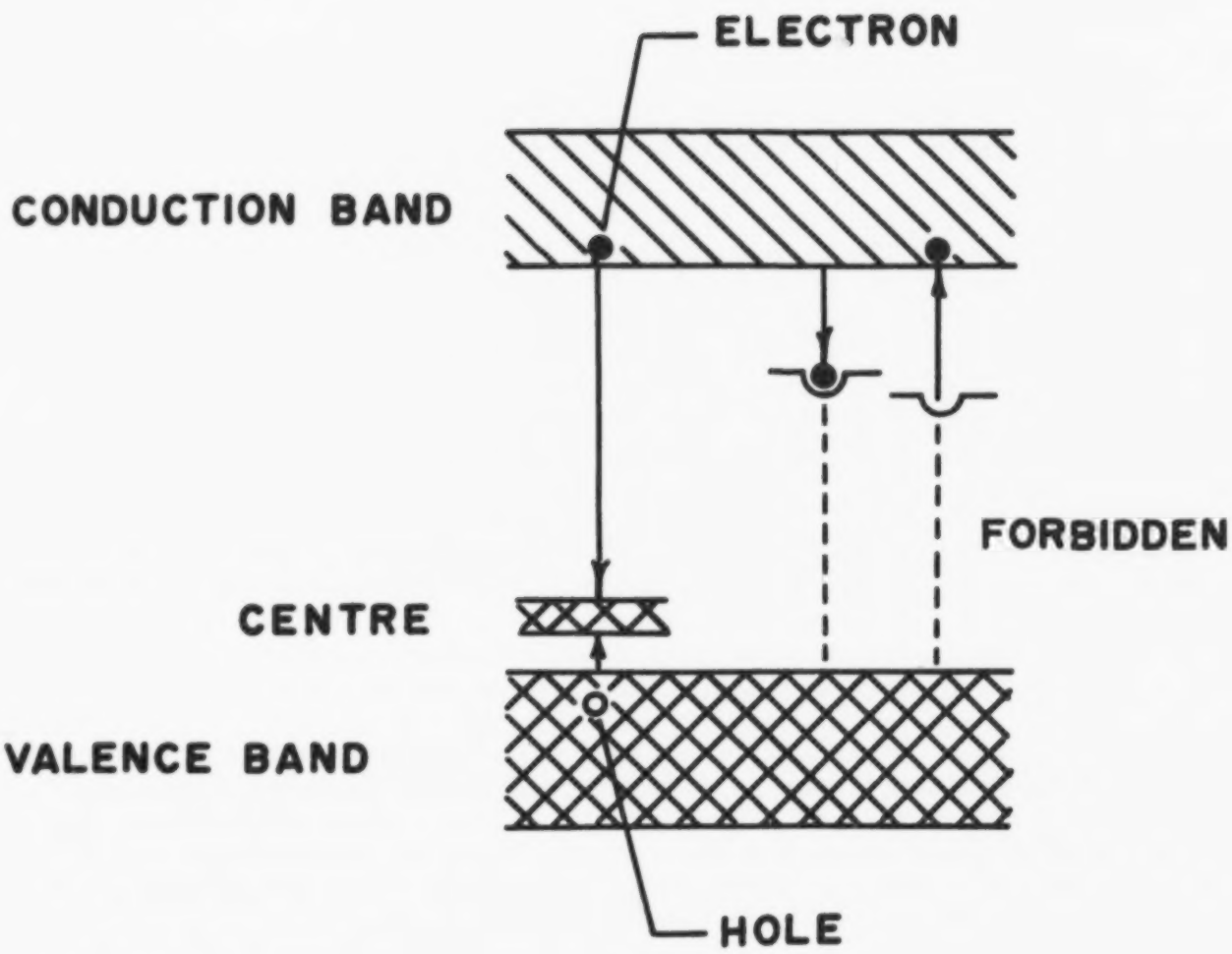


Figure 2. Photoconducting crystal

is relatively high. If the temperature is low, the transition will occur at a relatively slow rate or be completely "frozen in."

We can distinguish two types of fluorescent processes: monomolecular, associated with first-order kinetics; and bimolecular, associated with second-order kinetics.

If the fluorescent process is monomolecular, then first-order kinetics apply, and the fraction of electrons returning to the ground state in a specific unit of time, dt, is a constant. If n is the number of electrons in the excited state at time t and α is the decay constant for the crystal at a given temperature, then

$$\frac{-dn/dt}{n} = \alpha$$

$$\frac{dn}{n} = -\alpha\, dt$$

$$n = n_o e^{-\alpha t}$$

If I is defined as the luminescence decay then

$$I = \frac{dn}{dt} = - \alpha n$$

therefore

$$I = - \alpha n_o e^{- \alpha t}$$

$$I = I_o e^{- \alpha t}$$

As previously stated, the luminescence of most inorganic crystals depends upon the presence of impurity, or activator, atoms which establish centres in the forbidden energy band of the crystal. In this case the fraction of electrons returning to the ground state in a specific unit of time is proportional to the number of these available centres:

$$- \frac{dn/dt}{n} = \alpha n$$

$$\frac{dn}{n^2} = - \alpha dt$$

$$n = \frac{n_o}{(1+n_o \alpha t)}$$

and so, n decreases hyperbolically with time when second-order kinetics apply. The luminescence decay is then given by:

$$I = \frac{dn}{dt} = \alpha n^2$$

thus $$I = \frac{I_o}{(1+at)^2}$$

Where $$a = (I_o \ \alpha)^{1/2}$$

thus in the bimolecular case, decay becomes more rapid as the excitation intensity is increased.

The above kinetics applies exactly only to fluorescence since its derivation does not consider the intermediate process of trapping. For a particular crystal matrix, the observed luminescence is often a combination of monomolecular and bimolecular schemes with one or the other predominating.

In the case of sulfide phosphors of the type ZnS:Cu, the short duration emission seems to involve first of all a monomolecular decay with a lifetime characteristic of transitions in isolated atoms, and finally an approximately bimolecular decay with a lifetime of the order of 10^{-5} seconds due to electrons, previously liberated, recombining with emission centres. All this is followed by a slower decay (10^{-4} to 10^{-2} seconds) with complex kinetics and which is really a short period phosphorescence due to traps of 0.3 or 0.4 eV in depth. Finally, there follows a relatively long period of phosphorescence (4).

It is a characteristic of many inorganic phosphors for their luminescent response, when excited by X-rays, to increase as temperature is decreased. An electron in the valence band can enter a luminescent centre by thermal activation. The electron previously removed from the centre to the conduction band can no longer return to this centre, but instead can recombine via some other defect; quenching centre, for example. The same transition of an electron from the valence band to an activator level can occur by the absorption of an optical photon, i.e., optical quenching due to infrared radiation (4).

The action of a specific activator atom on the luminescent spectral emission of ZnS crystals has been shown by the work of Leverenz (15). The peak wave length of the luminescent emission band occurs in the following order for a cubical ZnS crystal:

ZnS:Ag - 4,550 A°, (2.73 eV)
ZnS:Zn - 4,700 A°, (2.64 eV)
ZnS:Cu - 5,280 A°, (2.35 eV)
ZnS:Mn - 5,910 A°, (2.1 eV)

The major visible luminescence is, as previously described, due to the transition of an electron in the conduction band to an activator level. This can diagrammatically be shown for the specified ZnS crystals in figure 3.

In this simplified energy-level picture at least two possibilities have been ignored: electrons might fall from the conduction band to normally unoccupied impurity levels, such as E_I, before making the transition to the lower energy states; secondly, the electron might be raised initially to the discrete, unoccupied level. Electrons raised to these band excitation states are not free to move throughout the crystal. An example of this type of transition is shown by the ZnS:Mn phosphor whose luminescence is primarily due to transitions within bound excitation states.

In all cases where luminescence is of importance the measurement of luminescent efficiency must be considered. There are three ways of defining the efficiency of a luminescent light source: (1) Luminous efficiencey; the ratio of the total light output to the energy input without questioning which part of this energy is absorbed by the luminescent material or lost by reflection, transmission or by an other process. (2) Energy yield, ϕ ; the ratio of the energy of the luminescent light, in ergs or watts per second, to the energy abosrbed by the luminescent material. (3) Quantum yield, Q; the ratio of the number of photons absorbed by the luminescent material to the number of photons contained in the emitted light.

The effect of the specific spectral distribution of a particular phosphor on its luminescent efficiency has been graphically demonstrated by Leverenz (15). In the lower curves of figure 4 are shown the relative energy versus wave length for ZnS and Zn-CdS phosphors. It can be observed that on an energy basis, the ZnS is the most efficient, however, when physiological considerations are taken into account the Zn-CdS is the phosphor of choice.

Peckham (26) has demonstrated by use of a psychometric technique, that measures the resolving power of fluoroscopic screens at various contrast and brightness levels, the optimum composition for a fluoroscopic screen. A phosphor ratio of 55 parts of Zinc Sulfide to 45 parts of Cadmium Sulfide was found to be optimum. An increase in phosphor thickness will result in greater light output.

This greater thickness also results in a reduction of the resolving power of the screen due to scatter of the light in the thicker phosphor layer. For the screens studied, he found a thickness of 0.0125 inches to be optimum.

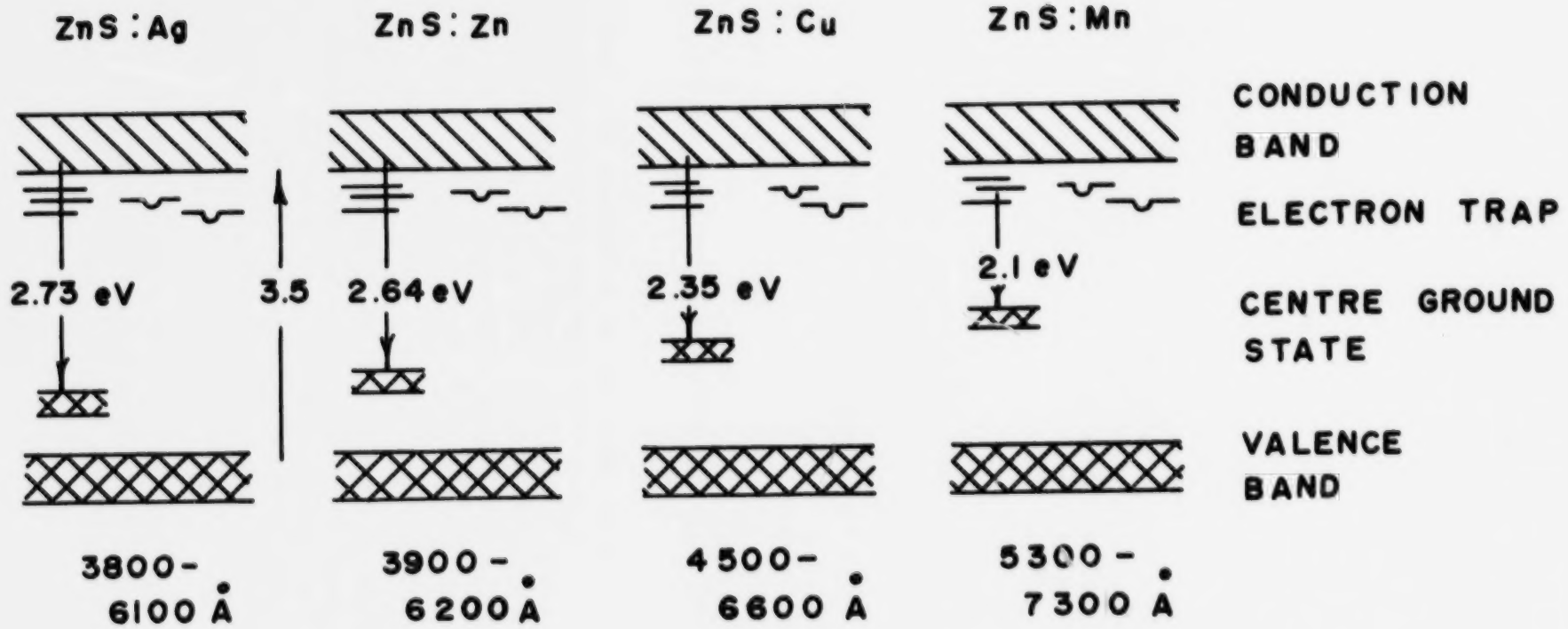


Figure 3. Effect of different activator atoms in zinc sulfide crystal matrix

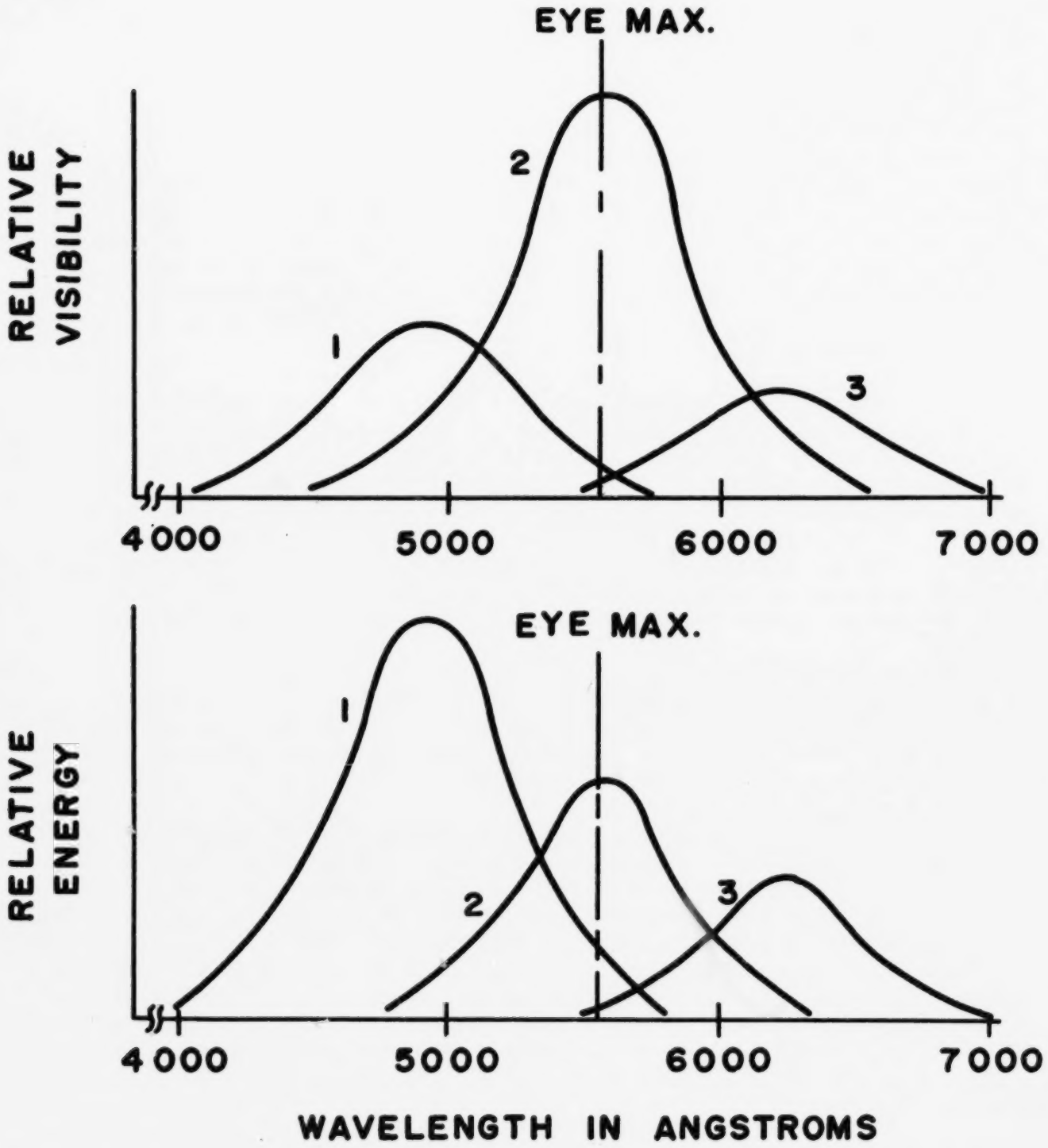


Figure 4. Spectral distribution of energy and relative visibility for (1) ZnS:Ag, (2) Zn(50%)-Cd(50%)S:Ag, and (3) Zn(20%)-Cd(80%)S:Ag

IV. FLUORESCENT DETERIORATION REPORTED

There has been very little quantitative information concerning the permanent deterioration of the luminescent capabilities of fluorescent screens. While working with calcium tungstate, $CaWO_4$, intensifying screens Coltman, Ebbighausen and Alter (3) observed that the portion of the screen that had been exposed to X-rays was somewhat fainter. They classified this deterioration of luminescence as screen "fatigue." In their experimentation, the screen had been exposed to an 80 kilovolt, 20 milliampere X-ray beam filtered by one-half millimeter of copper. The screen was mounted over a 2-inch square hole in a sheet of 1/8-inch lead. This lead shield and screen were mounted over the open end of an X-ray protective cone of unspecified dimensions. The screen was exposed for a period of about 6-1/2 hours under the above mentioned conditions.

The reported measurements indicated that the exposed portion of the screen was about 8% "fainter" than the outer portion that had been protected from the high exposure levels by the 1/8-inch lead shield. This observation indicates that a deterioration of calcium tungstate may be expected from extended exposure to X-rays of a typical diagnostic energy. It should be kept in mind that the exposure time involved exceeds any normal medical usage. The luminescent process in the inorganic calcium tungstate crystal is similar to that observed in zinc-cadium sulfide-type phosphors, so a similar effect might take place for this phosphor.

A study of the blackening of zinc and cadmium sulfide phosphors when exposed to visible light has been reported by Gordon, Seitz and Quinlin (7). From their work and others, they drew the following conclusions concerning photoluminescent zinc sulfide:

A. Only sulfides that are photoluminescent will darken appreciably under the influence of ultraviolet radiation. In the preparation of these crystals, they were first precipitated from an aqueous solution and then heat treated. The heat treatment, consisting of one hour in a 950°C oven, was necessary to render the phosphor luminescent. The effect of this heat treatment was the introduction of neutral zinc or cadmium atoms into the crystal lattice. These interstitial atoms, which are not part of the regular crystal lattice, create luminescent centres. Only after the heat treatment had caused the introduction of these interstitial atoms was ultraviolet radiation capable of producing any appreciable darkening of the phosphor.

B. They were able to further correlate the darkening of the phosphor with the presence of the luminescent centres by subjecting the crystals to high pressures. Under normal conditions the interstitial atoms were thought to be in thermodynamic equilibrium with their surroundings; the pressure would cause a condition of unbalance allowing the interstitial

atoms to precipitate out. When this occurred, the phosphor lost its capability to fluoresce and no further appreciable darkening occurred.

C. Moisture was found to accelerate the darkening process by a factor of a thousand or more over that experienced in a dry environment. Zinc-cadmium sulfide contained in an evacuated quart container was exposed to a mercury vapor lamp for a period of 2,000 hours. No appreciable darkening was observed during this period. A similar sample, exposed to the same light source but in a supersaturated atmosphere, became very dark in less than one-half hour.

In the process of photoluminescence, an electron is first raised to the conduction band by the absorption of energy from the incident light photons. This freed electron will either recombine with a luminescent centre producing fluorescent light, or will become trapped. In a vacuum the trapped electron can, in time, gain sufficient thermal energy and escape the trap. In the presence of moisture the negative charge of the trap would attract a positive ion and render the trap stable. The positive ions are postulated to be zinc ions of dissolved zinc sulfide in the situation where pure water is present. The concentration of ions would be much greater if a good electrolyte were present and, in fact, Gordon, Seitz and Quinlin (7) found that exposure of the phosphor while in a sodium chloride solution would cause the darkening to proceed at a faster rate than that observed for pure water.

In phosphor excitation, an electron is raised to the conduction band leaving a free positive hole in the valence band. This hole will migrate in the crystal and, upon reaching the surface, will act like singly-charged sulfur atoms attracting negatively charged ions from the solution. According to this description, the interior of the zinc sulfide crystal should be left unaltered in the final state since the centres are not depleted during blackening, but act as catalysts. This is borne out by the fact that centre concentration can be of the order of 10^{-4} of the concentration of the ordinary atoms in the crystals, but decomposition of more than 10% of the atoms can be obtained.

The creation of free zinc and sulfur may be looked upon as the electrolysis of zinc sulfide by the electromotive force created by the ionic crystal structure. Gordon, Seitz and Quinlin (7) have postulated that the following process may be plausible:

$$2\,Zn^{+} \rightarrow Zn^{++} + Zn$$
$$2\,S^{-} \rightarrow S^{--} + S$$

Under the correct conditions, the above process is reversible ($Zn + S \rightarrow ZnS$). They found that a slightly darkened sample of zinc sulfide reverted to its original state if left in the dark. This reversal also required a moist condition and was accelerated by the presence of an electrolyte.

The decomposition products have been analyzed and consist mainly of free zinc and sulfur with traces of H_2S, SO_2 and hydrosulfuric acids. The compounds can be explained by the presence of water. Some of these products, for example the free zinc and sulfur, may revert to their original state as a zinc sulfide crystal, but this may not always be a 100% reversal. Other products formed, such as H_2S and SO_2, may not be capable of ever reverting to their original state.

In summary, Gordon, Seitz and Quinlin (7) have shown that under the influence of light, moisture and pressure, zinc and cadmium sulfide crystals will darken. The process is usually not 100% reversible, in which case the overall effect would be a permanent darkening of the luminescent material. Even for the 100% reversible process, there is no assurance that the material would be returned to its original crystal lattice state, in which case the luminous efficiency might be expected to change.

Curie (4) states that daylight will produce a blackening of zinc sulfide and of cadmium sulfide. Like Gordon, Seitz and Quinlin, he attributes this darkening to the production of free metal atoms. He assumes the mechanism is a photochemical process which breaks the atomic bond holding the atom in the crystal lattice; the metal becomes colloidal and the damage is irreversible.

The luminescent process can be subdivided according to the excitation process. Photoluminescence occurs when the material, usually of crystalline structure, is excited by the absorption of light. It may be assumed that each quantum of light excites one electron. According to quantum theory, the quantum $h\nu$ must correspond to the energy difference ΔE between the ground state and the particular excited state. The frequence of the emitted luminescent radiation is dependent upon the energy difference between the ground and excited state and is uniquely determined for a particular material.

For excitation by ionizing radiation, X-rays, gamma rays, electrons, etc., the situation is somewhat more complicated. Cathodeluminescence deals with luminescent exciation by cathode rays, electrons such as used in cathode-ray tubes, etc. X-ray excitation will first involve a photoelectric, Compton or pair production reaction producing charged particles that will act like the cathode rays. Each particle penetrates into the solid losing energy in collisions with the electrons of the crystal and thus causing the excitation of a number of secondary electrons. The nature of the luminescence is the same for both types of excitation, the energy of the luminescent radiation being determined solely by the energy states of the material.

Very little has been reported concerning the possible deterioration of zinc sulfide type phosphors under the influence of X-ray exposure. In X-ray excitation, although the primary radiation consists of photons, the

excitation is due to the fast secondary electrons. X-ray excited luminescence approaches more nearly cathodeluminescence than it does photoluminescence. A consideration of the results obtained from the studies involving cathodeluminescence should give more insight into the possible effects due to X-rays.

Due to its wide utilization in the electronic image tube in recent years, cathodeluminescence has been studied by a number of investigators. In cathodeluminescence, the ionizing particle, the electron, passing through the phosphor excites or ionizes the crystal atoms; this excitation is followed by the emission of visible fluorescence. Cathode ray excitation is accompanied by a strong perturbation of the entire crystal lattice; even electrons in the inner atomic shells may be excited by the incident particles. This process is much more complex than that taking place in photoexcitation where only the valence and conduction bands are considered.

The radiative transition process whereby the visible photons are released is usually independent of the mode of excitation, for example in cathodeluminescence, the same emission spectrum is obtained as in photoluminescence. Some difference will arise in the conversion efficiency, the value of efficiency being less for ionizing radiation than for photoexcitation by ultraviolet light. This variation between photoexcitation and cathode excitation is greatest for particulate radiation of high specific ionization and of high excitation density.

Smith, Potter and Aven (31) noted the effect of humidity on the deterioration of electroluminescent panels. They postulated that this effect is due, in part, to the rotation of the sulfide grains produced by the internal electric field of the dielectric and this, in turn, leads to a lowering of the luminescence efficiency.

For ionizing radiation of sufficient energy there is the possibility of producing lattice defects and interstitial atoms in the crystal matrix (14). This requires an energy of about 8.7 electron volts in cadmium sulfide corresponding to a minimum threshold energy of 115 thousand electron volts for the bombarding electrons. In zinc sulfide, the minimum value is probably about 15 electron volts. When the energy is greater than this minimum threshold value, the possibility of creating new centres is initiated.

Curie (4) states that zinc sulfide and cadmium sulfide subjected to electron bombardment slowly blackens and the luminescent efficiency decreases. He states that this effect is, in part, due to the production of non-radiative recombination centres.

V. X-RAY APPARATUS AND INSTRUMENTATION

A special arrangement consisting of an X-ray unit together with housing was constructed for this study. The intent was to have a self-shielded, self-contained unit in which exposure conditions, similar to those of a conventional fluoroscopic unit, could be obtained and for which the geometry would be fixed so that reproducible results could be obtained over a long term study.

The apparatus, see figures 5 and 6, employs a General Electric Maximar-100 X-ray unit housed in a shielded enclosure constructed of lead bonded to plywood. The tube head is mounted in the shielded enclosure with the beam port facing upward. The control is mounted on the side of the shielded enclosure. The unit has a continually-variable kilovoltage control and a maximum energy of 100 kilovolts peak. A current stabilizer with six-position switch is built into the unit so that non-fluctuating current settings from one-half to five milliamperes can be obtained.

The internal dimensions of the unit are shown in figure 7. A piece of fluoroscopic table top is mounted 20 inches above the focal spot and the focal-screen distance is 30 inches. Two doors allow access to the area directly above the table top position so that various thicknesses of tissue-equivalent material may be placed in the primary beam at this site where the patient is normally positioned. The fluoroscopic screens are mounted 10 inches above the table top. When the unit is to be used for fluorescent light measurements, a special adapter--constructed of 1/16-inch steel--is used to hold the detector portion of the "Brightness Spot Meter" and one of the 5 inch by 7 inch fluoroscopic screen assemblies consisting of a fluoroscopic screen with lead-glass and cardboard backing. This adapter provides a light tight coupling between the screen and light meter so that measurements of screen luminescence can be made in the convenience of a fully-lighted room. When the X-ray unit is used to irradiate the screens, as part of the controlled test exposure, a second adapter is used. This adapter holds four of the 5 inch by 7 inch fluoroscopic screen assemblies consisting of a screen with lead-glass cover and cardboard backing.

When the table top access doors are open, a panel hinged at the base may be opened to allow access to the tube head. This is to allow ease in changing the filters and cones used with this unit. The doors and head-access panel are interlocked with the control to prevent operation of the unit when they are open.

The Maximar-100 X-ray unit has a two millimeter thick beryllium window tube for which the equivalent aluminum thickness is less than 0.1 millimeters. An additional 2.5 millimeter aluminum filter was placed in the beam at the filter position on the tube head. In addition,

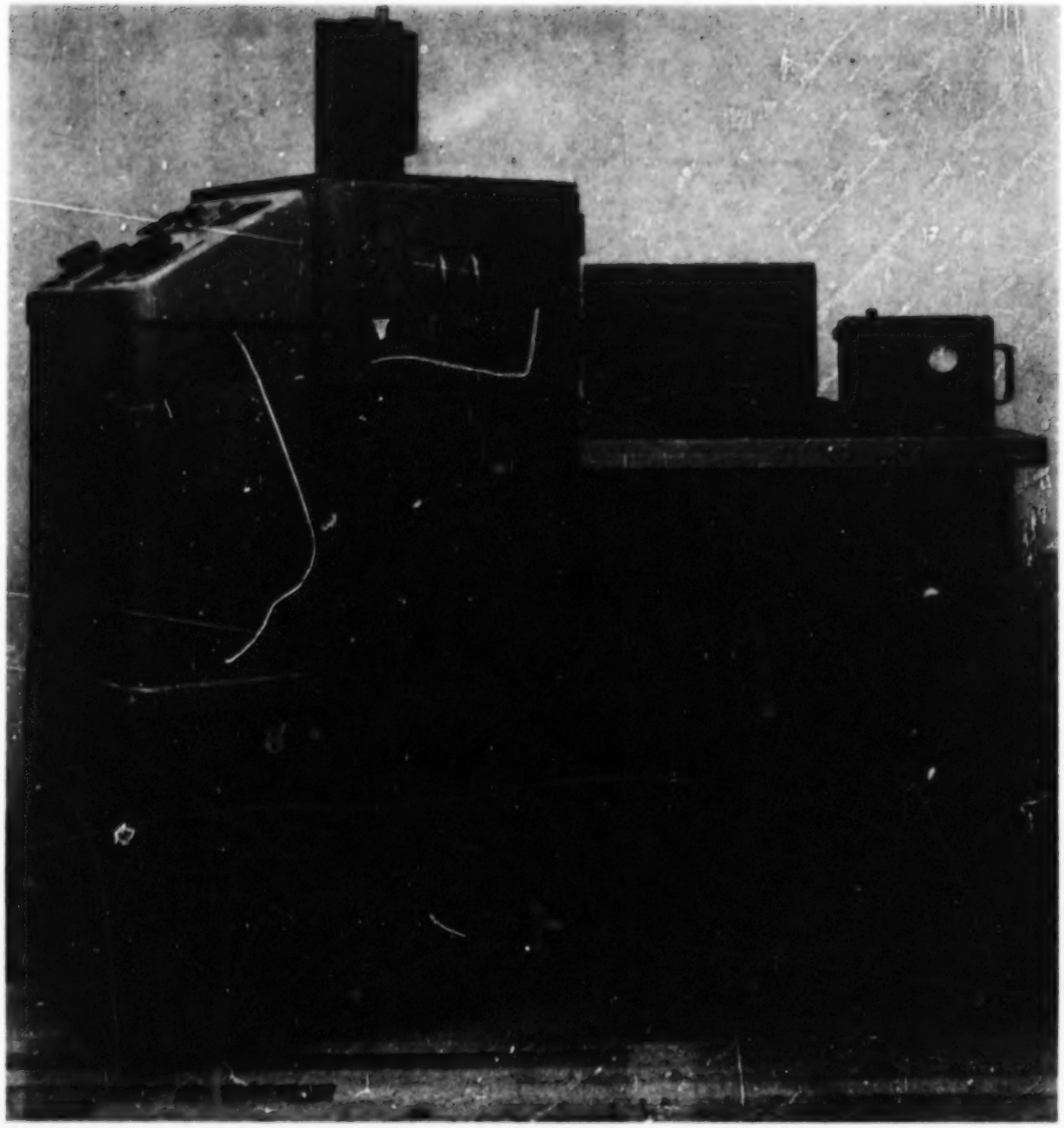


Figure 5. Special X-ray unit with "Brightness Spot Meter" mounted on adapter

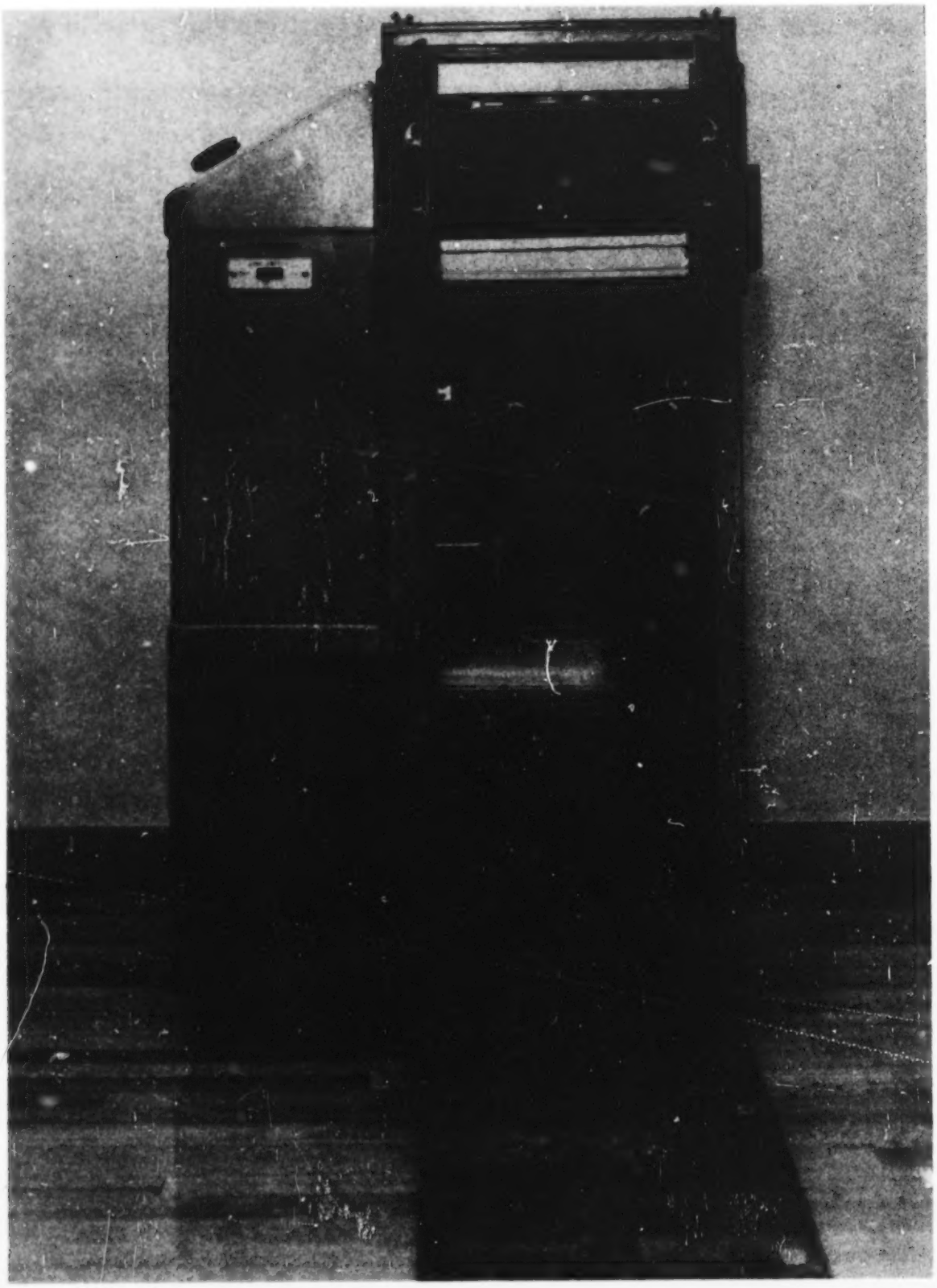


Figure 6. Special X-ray unit with front panels open and screen exposure holder intercepting the beam

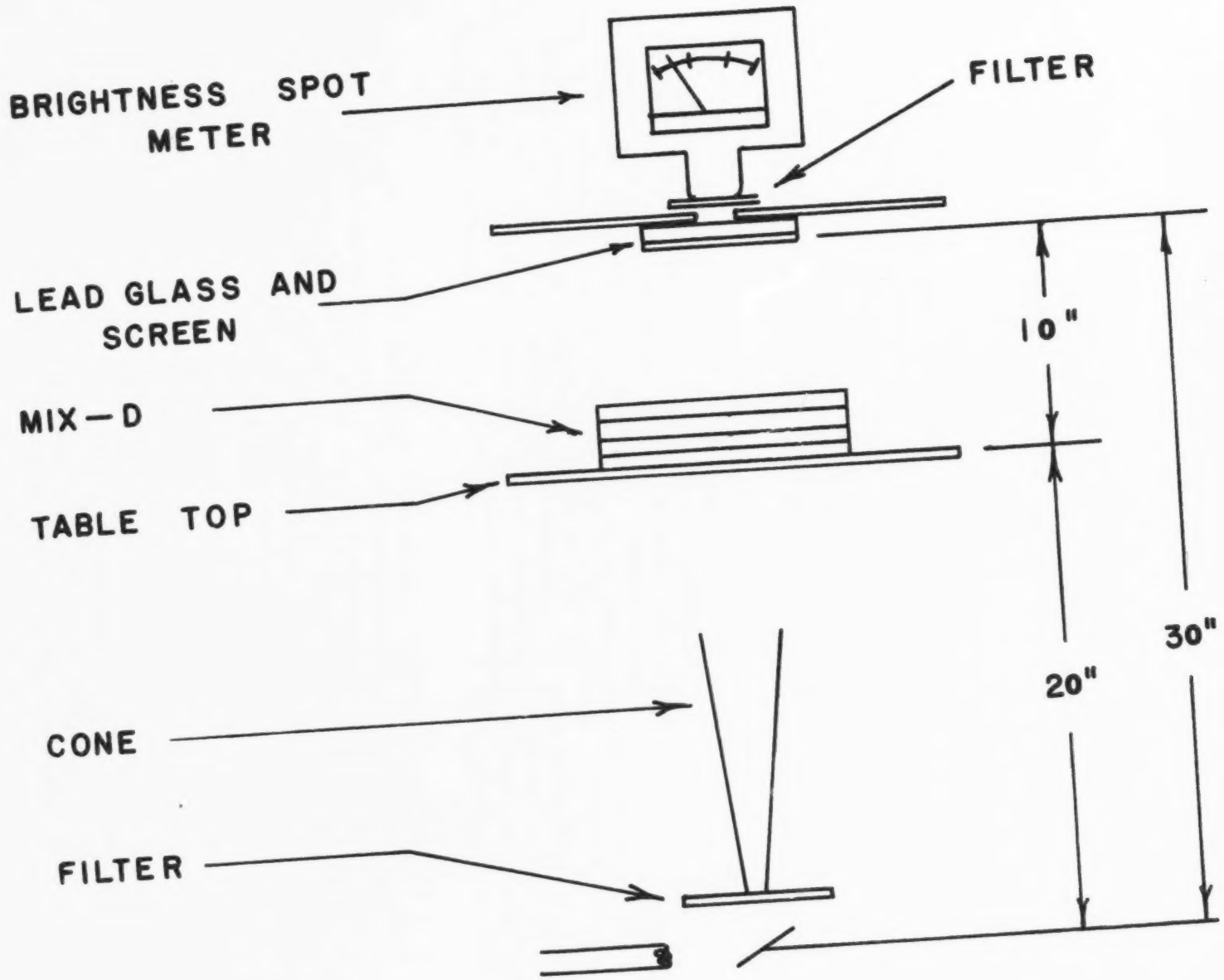


Figure 7. Geometry of special X-ray setup

there is the filtration of the table top making the total filtration in excess of the recommendations of the National Council on Radiation Protection and Measurement (NCRP) Handbook No. 76. Measurements made with a Victoreen condenser R-meter at the table top at 100 kVp gave a "unique" half-value layer of 3.38 millimeters of aluminum and a homogeneity coefficient of 0.884 (37).

The measured exposure rate per minute at the table top is shown in figure 8. All values of exposure rate are seen to be less than 10 roentgens per minute, the maximum exposure rate recommended by the NCRP (38).

When measurements of the luminescent response of the fluoroscopic screens are made, three sheets of one-half-inch thick MIX-D (12), a tissue-equivalent phantom material, is placed at the table top position. The measured exposure rate per minute at the screen position is shown in figure 9. These measurements were made with a Victoreen condenser R-meter. The filtration was as specified above and a cone, limiting the beam to a five centimeter diameter at a distance of 30 centimeters from the focal spot, was used.

Light level measurements were made with a Photo Research Corporation Spectra "Brightness Spot Meter," Model UB-1-1/2°. This meter is a direct-reading instrument eliminating the error inherent in techniques employing the visual matching of brightness levels. Light is picked up by an f-1.9 objective lens. A partial reflecting mirror located in the interior of the lens system directs a portion of the light downward to a sensing photomultiplier tube. Output from the photomultiplier tube is fed to the input grid resistor and range-selector circuit of a three-stage DC electrometer tube amplifier. The output signal is indicated on a microammeter calibrated in footlamberts brightness.

The Spot Meter has an optical acceptance angle of 1-1/2°. The minimun range full scale is 0.01 footlamberts and the minimum detectable brightness 0.0001 footlamberts. Calibration is maintained by use of a regulated brightness source supplied by the same manufacturer. According to the manufacturer's specifications, this calibration source of nine footlamberts has a rated variation of $\pm$ 1% when operated from a 95-130 volt, 60 H_z line.

To measure luminous intensity, the photo tube S-4* response characteristic has been modified by insertion of a Wratten 106 filter to simulate the International Commission on Illumination (C.I.E.), luminous response curve. The C.I.E. values are the variation of photopic luminous efficiency with light wave length as established for the human eye by the C.I.E. (39). The C.I.E. luminosity response and response of the Spot Meter are shown in figure 10.

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*Designation of photodetector spectral response established by the Electronic Industries Association (E.I.A.)

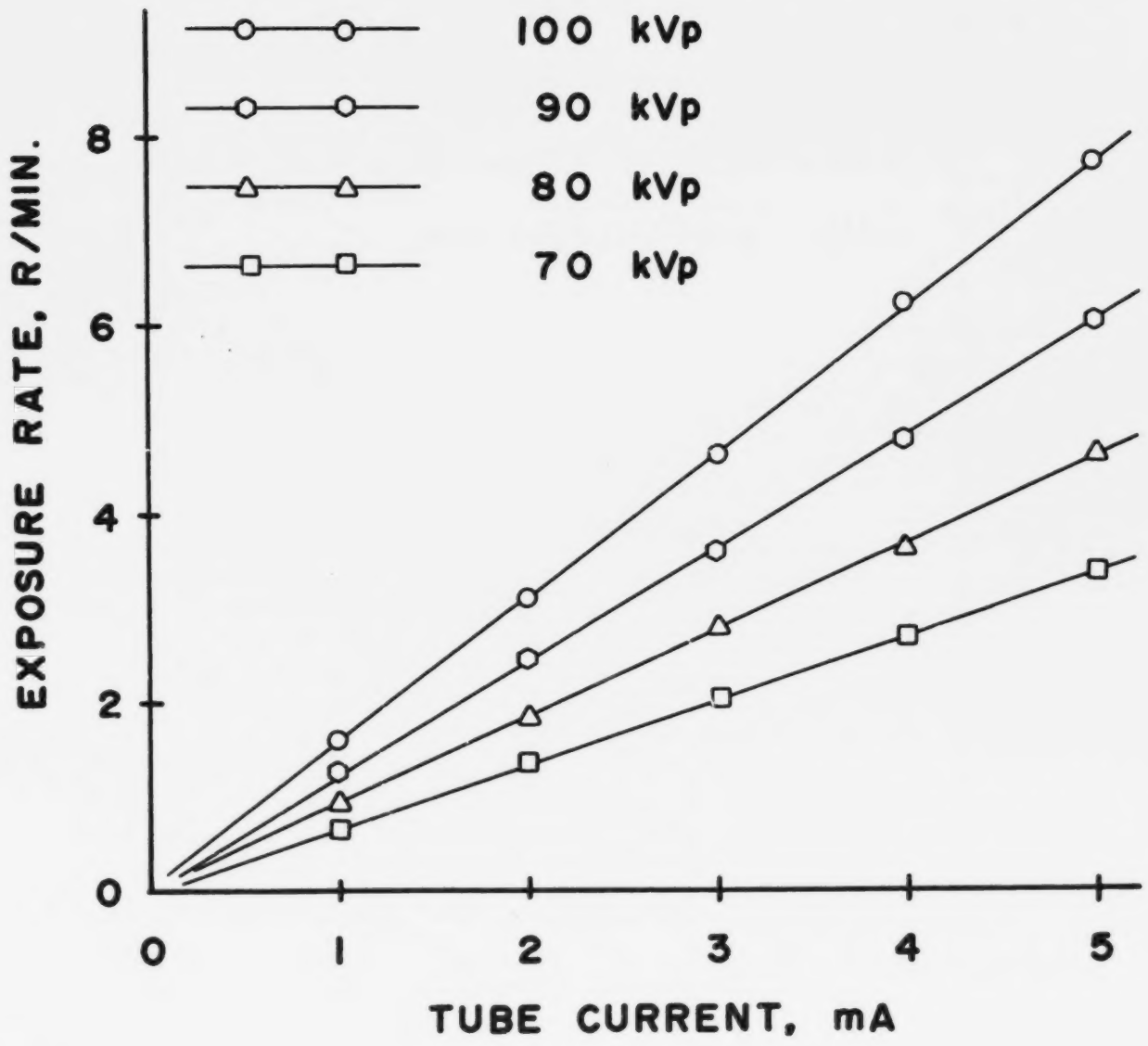

Figure 8. Table top exposure rate versus tube current for special X-ray unit

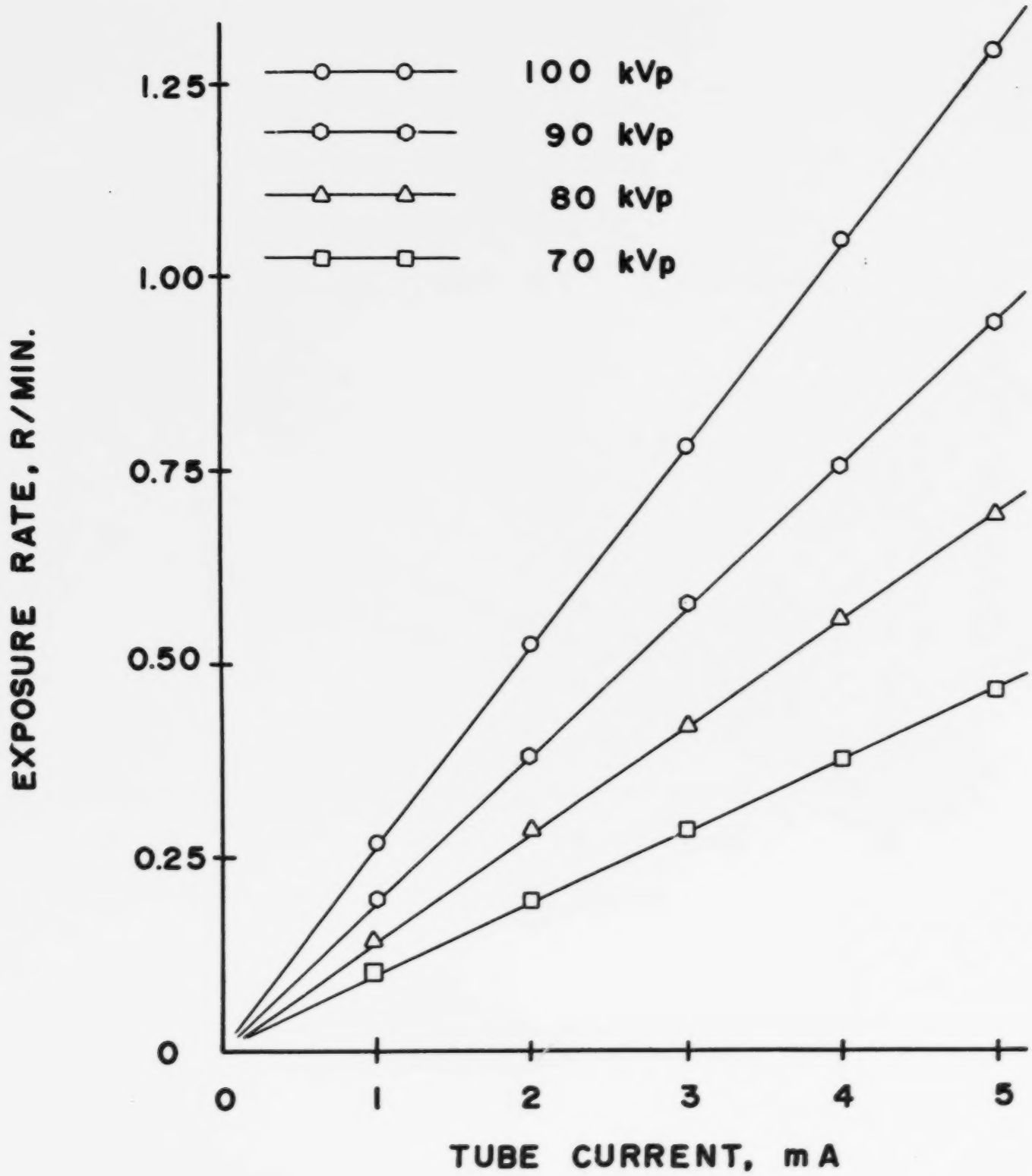

Figure 9. Screen exposure rate versus tube current with 3 sheets of 1/2-inch-thick Mix-D in the beam

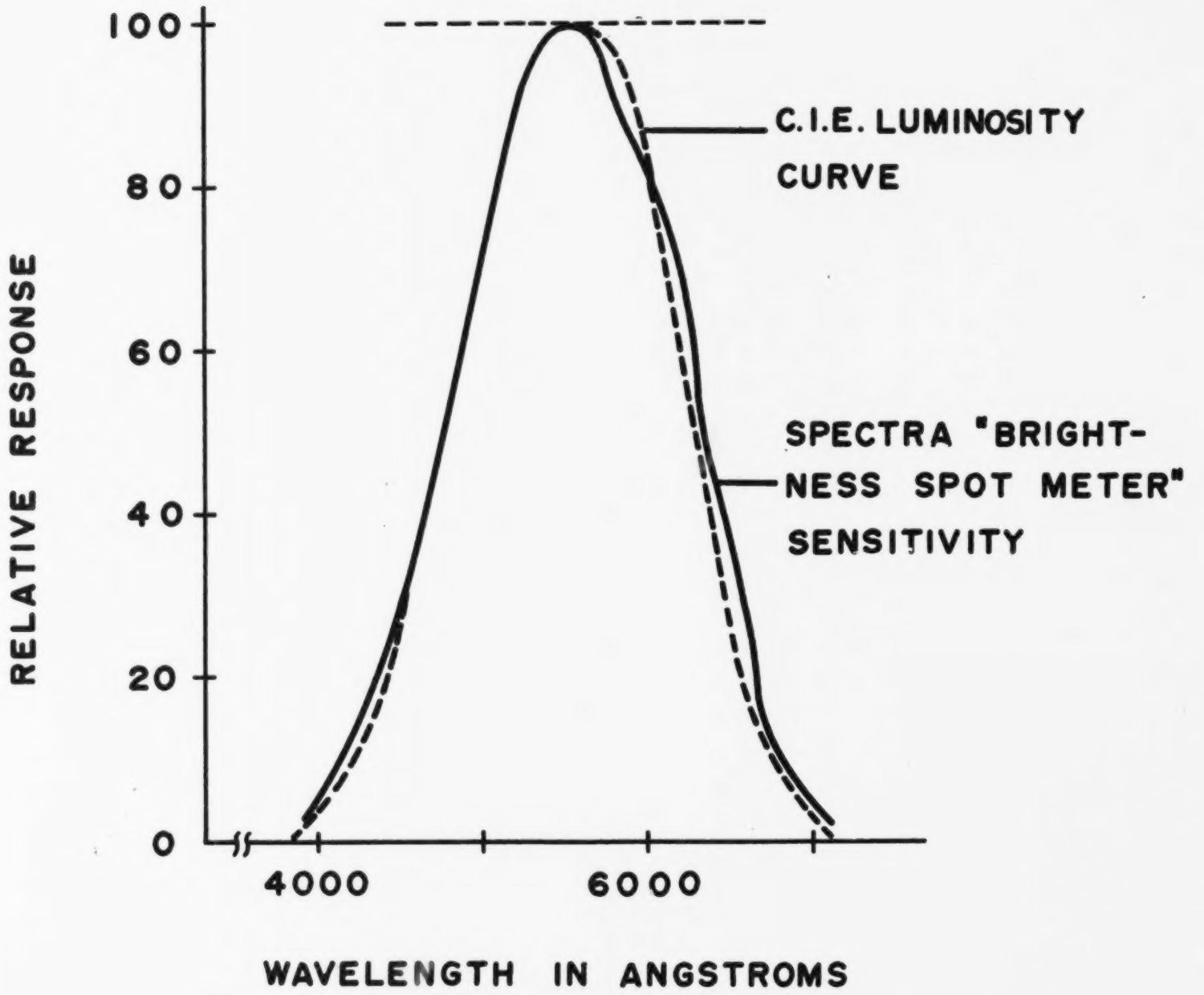

Figure 10. Comparison of C.I.E. luminosity curve and spectra "Brightness Spot Meter" sensitivity

As pointed out by the manufacturer of the Spot Meter, there are two limiting factors in producing an instrument capable of performing this transition exactly: first, the difficulty in producing the dye composition for the filter such that it will correct an S-4 detector characteristic to simulate the C.I.E. tristimulus values exactly. Secondly, the spectral characteristics of the detectors vary one from the other; thus necessitating individual correction filters for each instrument.

At the light levels experienced under conventional fluoroscopy the response is that of the scotopic eye. No correction has been made for this difference since the appropriate correction filters were not available.

VI. EXPOSURE CONDITIONS AND LUMINESCENT RESPONSE

Twenty-four fluoroscopic screens; 12 each from two different manufacturers, to be known as group I and group II, constitute the test population. These screens are 5 inches by 7 inches in size and consist of a zinc-cadmium sulfide phosphor applied to a plastic support backing. Measurements of the 12 group II screens gave an average light output response 18% greater than the average of the 12 group I screens. Variations in the measured light output among screens within each group of 12 were observed to vary $\pm$ 5% from the calculated average.

The manufacturers of both screens state that certain factors may cause a deterioration of the phosphor material. Specifically, manufacturer I states that the phosphor material from which his screens are made will discolor when exposed to ultraviolet radiation and should not be exposed to direct sunlight, bright daylight, ultraviolet or fluorescent lamps. He, therefore, recommends that these screens be covered at all times when not in use. Manufacturer II states that normal exposure to X-radiation does not damage the screens; but, since prolonged exposure to ultraviolet radiation of certain wave lengths may cause discoloration and reduce efficiency, it is recommended that exposure to light be kept to a minimum. In neither case does the manufacturer state whether these precautions apply to an unmounted screen or to a screen assembly incorporating lead glass which acts as a filter that removes most of the ultraviolet from the spectrum.

To study and, if possible, quantitate the effect of some of these factors, the population of test screens was divided into six groups, each group containing two screens from manufacturer I and two from manufacturer II. The division of the screens is shown in table 1. Each of the test conditions listed was chosen to investigate one of the agents reported or suspected of causing screen deterioration. All test conditions were designed to represent an exposure to the screen that could be interpreted in some realistic manner. For example; the exposure of the screens to sunlight, light from fluorescent and tungsten lamps was made through lead glass.

Table 1. Division of fluoroscopic screen test population

Exposure condition	Group I	Group II
A. Control	2	2
B. Busy diagnostic exposure	2	2
C. High radiation exposure	2	2
D. Fluorescent light exposure	2	2
E. Tungsten light exposure	2	2
F. Sunlight exposure	2	2

Table 2, below, is a tabulation of transmission factors supplied by the manufacturer for the lead glass used in this study.

Table 2. Ultraviolet transmission factors for nominal 6.35 mm lead glass

Wave length (microns)	Transmission factor
0.400	36%
0.390	20%
0.380	10%
0.370	03%
0.360	01%
0.350	00%

We have made spectrographic measurements of light transmission using a Hitachi Perkin-Elmer Spectrophotometer Model 139. Our data shown in figure 10A are in good agreement with the data in table 2.

All X-ray exposures were made with the screens placed next to lead glass so that backscatter conditions would be the same as those experienced by a fluoroscopic screen in a fluoroscopic screen assembly.

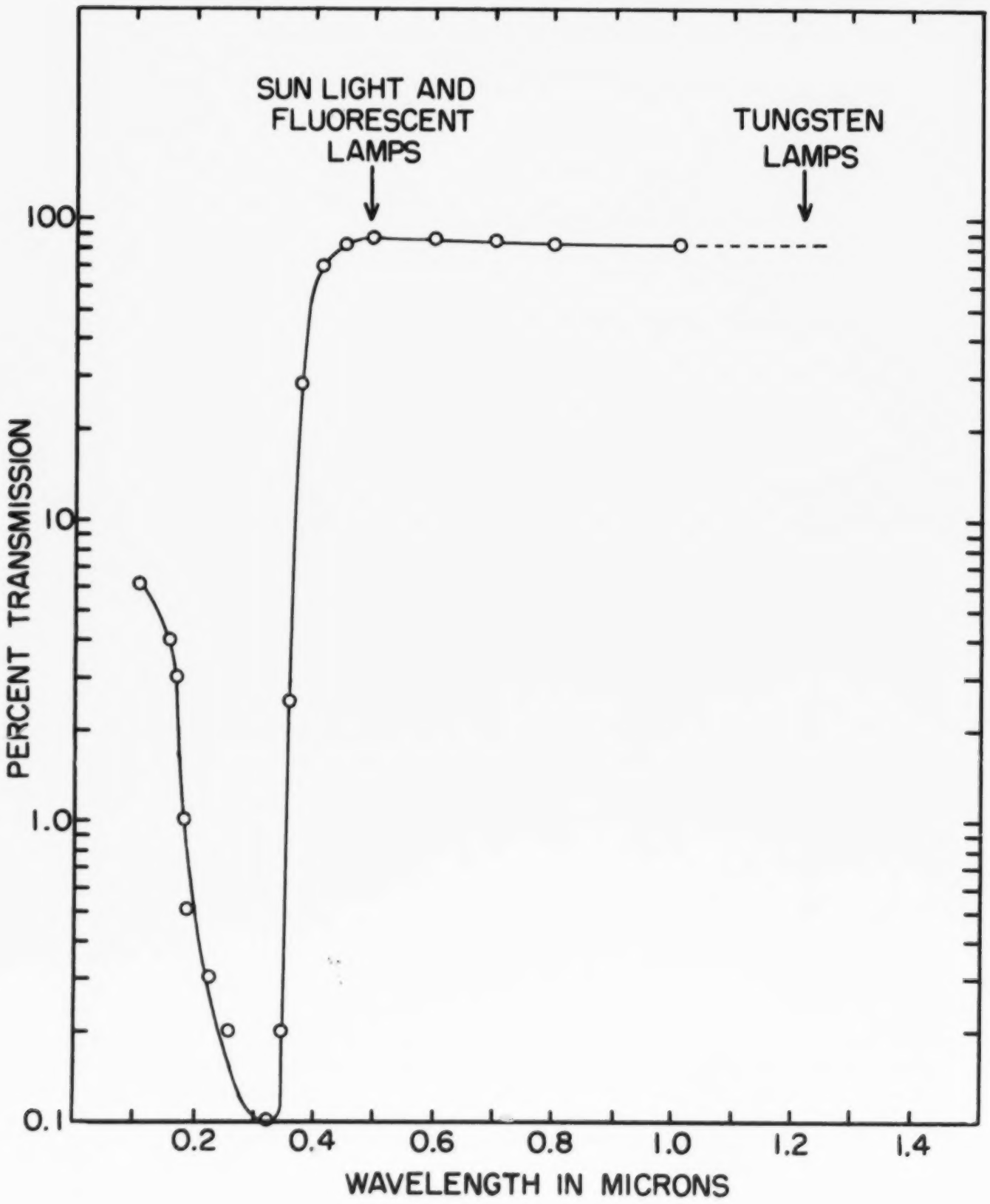

Figure 10A. Percent transmission of light through 6.35-millimeter-thick lead glass

Test conditions were as follows:

A. Control group; four screens kept in a darkened storage box at room temperature. These screens are retained at the laboratory and exposed to X-rays only when periodic measurements of the fluoroscent output of all the screens are made. This exposure is kept to the minimum consistent with data requirements.

B. Busy Diagnostic Exposure group; four screens exposed to 1,000 milliampere minutes per week. This exposure is made with the experimental X-ray unit operating at 100 kVp and five mA for which the exposure rate to the screen is 1.1 roentgens per minute. Four sheets of one-half inch thick MIX-D, a tissue-equivalent phantom material, are placed in the primary beam at the table top position between the X-ray tube and fluoroscopic screens. An interval timer provides an exposure cycle of 15 seconds ON and 15 seconds OFF to simulate conditions of actual usage. Again, it should be noted that all the screens are mounted in fluoroscopic assemblies including lead glass, equivalent to 2.0 mm of lead at 150 kVp, and a cardboard backing.

C. High Radiation Exposure group; four screens exposed to 1,000 milliampere minutes per week with no tissue-equivalent material in the beam. This exposure would represent the exposure received by a fluoroscopic screen subjected to an unattenuated direct beam.

This exposure was made with a General Electric Maxitron-300 X-ray unit operated at 100 kilovolts peak and 20 milliamperes. The filtration was equivalent to 2.5 millimeters of aluminum at the specified operating potential. As in the busy diagnostic exposure, the screens are incorporated into a fluoroscopic assembly. At the 80 centimeter target-to-screen distance used, the exposure rate is 23 roentgens per minute. Exposures are made once each week with no further attempt to fractionate the exposure.

D. Fluorescent Light Exposure group; four screens continually exposed to fluorescent light. The test was set up in an 18 ft by 9 ft room having no windows so that no external source of light would affect the test. The room contains two fluorescent light fixtures, each having four 40-watt daylight type fluorescent tubes. One group I and one group II screens are placed on a table top 31 inches from the floor and 75 inches from the light fixture. The level of illumination at this position was measured with a Weston Master III exposure meter and found to be 39 foot-candles. The two remaining screens in the test group are hung from the light fixture at a position 11 inches from the center of the fluorescent tubes. The measured illumination at this point was 300 foot-candles.

The spectrum of a daylight fluorescent lamp is shown in figure 11. Since light incident on all the fluoroscopic screens must pass through a sheet of lead glass, this factor must be considered. The transmission

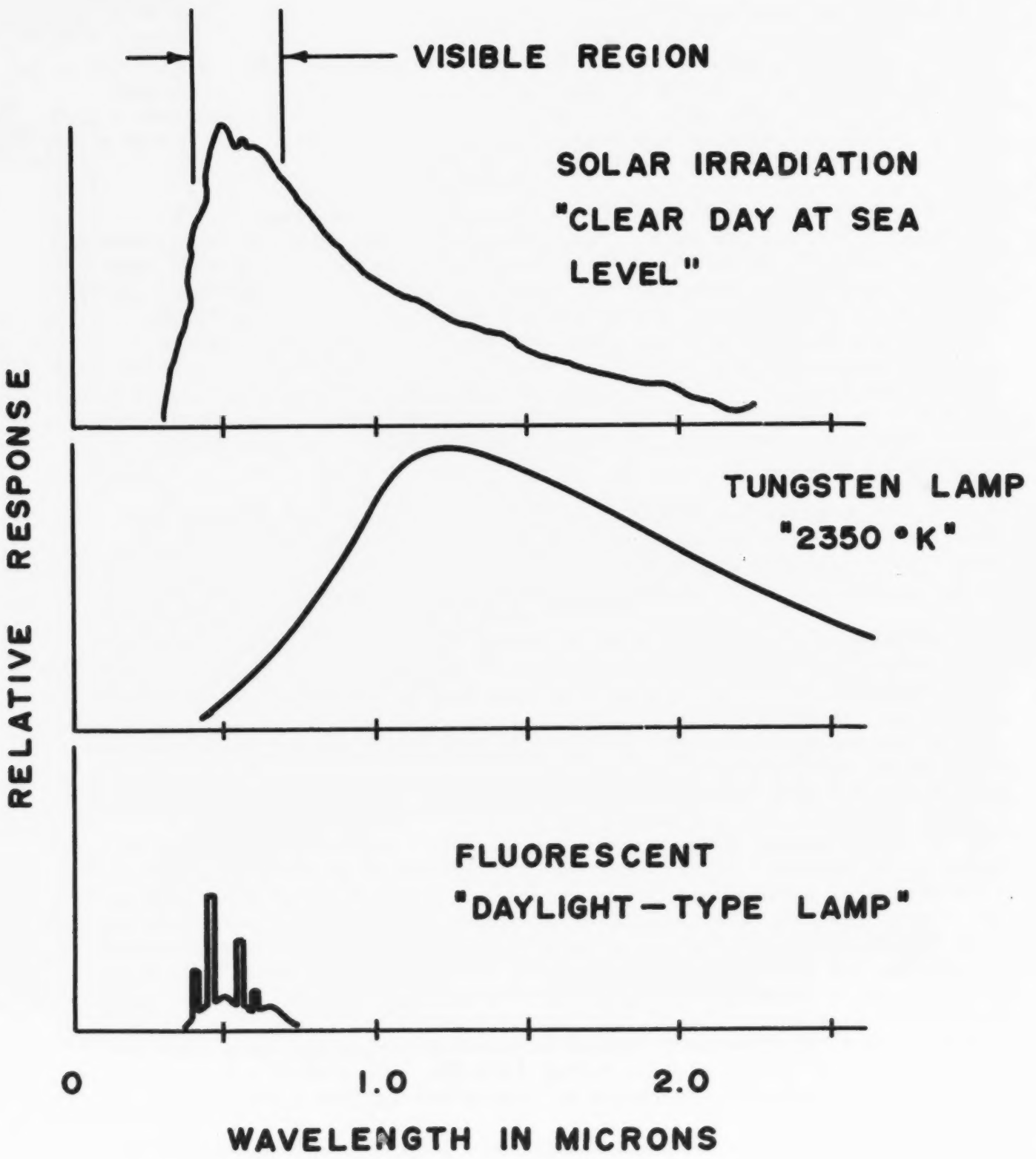

Figure 11. Typical light spectra from solar irradiation at sea level, tungsten lamp and daylight-type fluorescent lamp

characteristics of the glass would limit the ultraviolet portion of the spectrum received by the phosphor.

The normal recommended illumination levels, for a well-lighted room suitable for reading, range from 30 to 70 foot-candles. With these levels in mind, the measured illumination level of 39 foot-candles at the table top position could be considered a normal illumination level to which an uncovered screen might be exposed. The 300 foot-candle illumination level would be from five to ten times normal.

E. Tungsten Light Exposure group; four screens exposed continually to four 60-watt tungsten lamps operating on a nominal 115 volt line. Two screens, one group I and one group II, are placed seven inches from the lamps. The illumination level measured with the Weston Master III exposure meter is 300 foot-candles, a level five to ten times normal. Two screens at a distance of 21 inches from the lamps receive an illumination of 100 foot-candles.

F. Sunlight Exposure group; four screens exposed to direct sunlight in Las Vegas, Nevada. The fluoroscopic assemblies were sealed in a thin plastic bag to prevent possible damage due to moisture, sand, etc. The four screens comprising this test group were placed in an unshaded area and exposed to direct sunlight. Data on the number of hours of sunlight per day were obtained from the local U.S. Weather Bureau Station.

The Weather Bureau utilizes a pyranometer to obtain values for the number of hours of sunlight per day. The pyranometer is a thermal-response device consisting of two thermocouples connected in series with opposing polarities (13). A disk with a reflecting surface is connected to one thermocouple and another disk with a black surface is connected to the second. When sunlight is incident on the device, a signal is generated due to the higher temperature of the absorbing black surface. The temperature of the reflecting surface is an indication of the ambient conditions and would be equal to that of the black surface if no radiant energy were incident on it. The pyranometer measures only the flux scattered by the sky on a unit area normally to the sun at the earth's surface. A shield prevents direct sunlight from striking the instrument so that diffuse sky radiation is measured.

Following the last exposure period shown on the curves, the sunlight-exposed screens were subjected to violent and unplanned conditions. A driving rain strom caused the protective plastic bags to rip allowing the screens to get wet. This caused the screens to turn a gray-black color with an accompanied drop to almost zero in their luminescent output effiency. This effect noted is in agreement with the findings of Gordon, Seitz and Quinlin (7) previously described concerning the action of moisture on a zinc-cadmium sulfide phosphor.

Eight new screens (four group I and four group II) were obtained to replace the damaged sunlight exposure group. In order to eliminate the possibility of another act of nature ruining the screens, it was decided to expose them to artificial sunlight from a sunlamp.

The eight screens comprising this test group were placed 36" below a General Electric sunlamp. Four of the screens (two from group I and two from group II) were covered with lead glass. The remaining four screens were left uncovered so they were exposed directly to the light from the sunlamp. An interval timer was connected to the sunlamp that would allow one 8 hour exposure per day. The exposure to the screens was made with a Weston III exposure meter and found to be 100 foot-candles.

VII. LUMINESCENT RESPONSE

Measurements of the luminescent response, light output versus roentgen exposure, has been found to be a linear function over the range of exposure values used in this study. This is in agreement with Henny and Chamberlain (10). They reported that for a "type B" Patterson fluoroscopic screen a linear relationship exists between exposure at the screen and the corresponding brightness for exposure levels up to three or four roentgens per minute. It was shown in figure 9 that at 100 kilovolts peak and five milliamperes, the maximum operating values of the experimental X-ray unit, and with three sheets of MIX-D in the beam, the measured exposure rate at the screen was less than 1.5R/minute.

Figure 12 shows the characteristic response of a group I and group II fluoroscopic screen. The linear relationship between light output and exposure can be seen. These curves represent the average characteristic response of both groups of screens at 70 and 100 kilovolts.

VIII. EXPERIMENTAL DATA

At one month intervals, measurements of the characteristic light output response of all the fluoroscopic screens are taken. These measurements are made at 70 and 100 kilovolts peak and at each voltage six readings are taken, 0.5, 1, 2, 3, 4 and 5 mA. To minimize experimental error, all six readings are utilized in obtaining the light output of the screens at each test interval.

For each set of points describing the luminescent light output, a linear regression analysis is performed. This analysis is carried out on a Control Data Corporation, Model 3300 digital computer operated by the Oregon State University Computer Center. From each regression curve the light output, when excited by an exposure rate of 0.5R/minute, is determined.

Some variation can be observed in the luminescent output values measured at different reading dates. These variations were due to experimental and reading error. To demonstrate that these variations are due to experimental factors, the data taken on the same date for the control and test group screens are plotted on the same graph. Comparison of the curves shows that the control and test group variations are related.

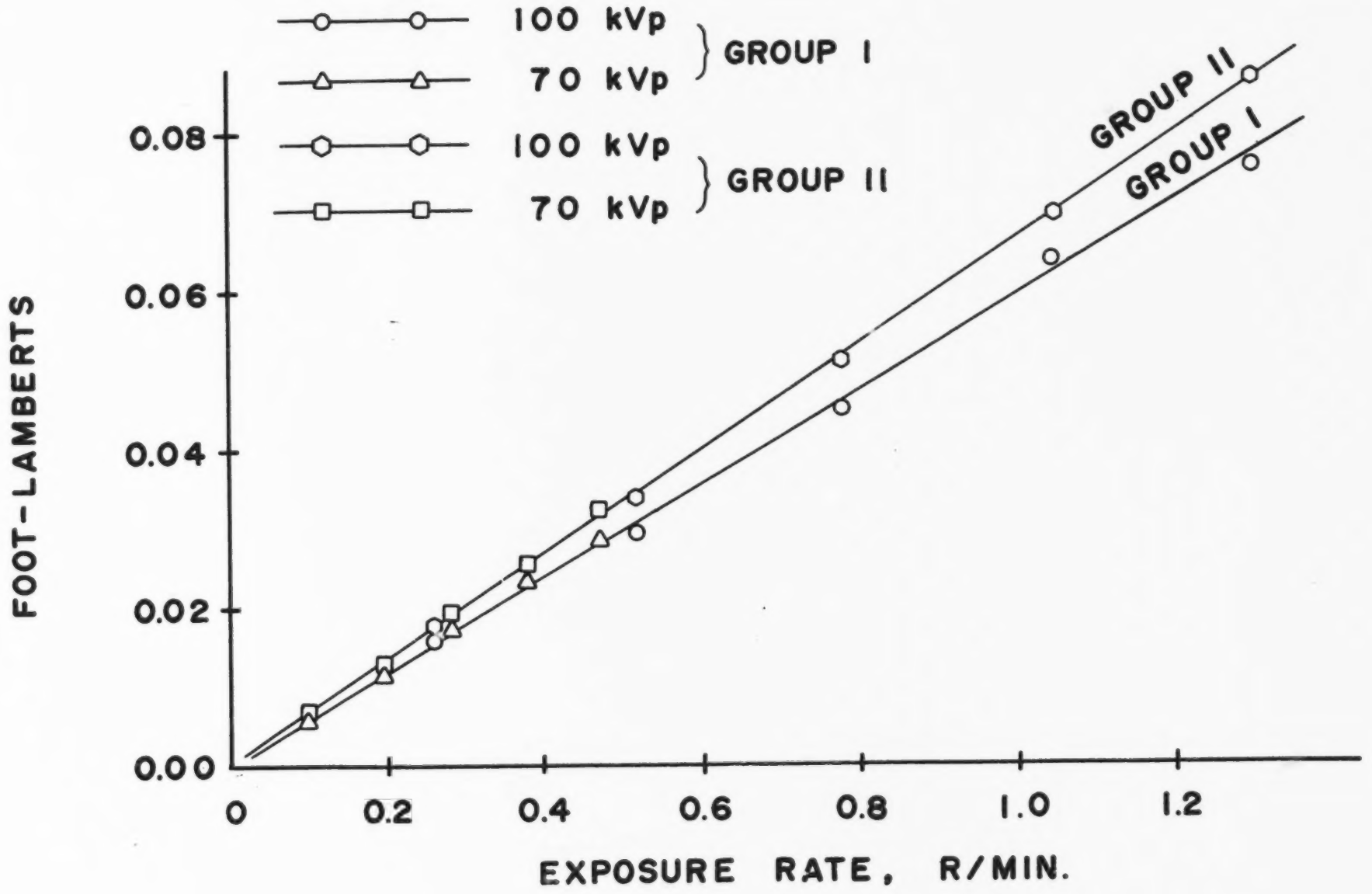

Figure 12. Foot-lamberts versus exposure rate for Group I and Group II fluoroscopic screens at 100 kVp and 70 kVp

The results of our study to date are shown in figures 13 through 16. These curves show the luminescent light output of the screens when exposed to 100 kVp X-rays at an exposure rate of one-half roentgen per minute. No difference between the 70 kVp and 100 kVp curves was found, so only the 100 kVp curves are presented here.

Figures 13A, 13B, 14A and 14B show the results obtained for the fluorescent and tungsten light exposure. Figure 15 shows the relative condition of the busy diagnostic and high radiation test group as a function of the number of weeks of exposure received. Figure 16A presents the data collected for the sunlight exposed screens prior to their damage due to rain and figure 16B shows the results obtained for the sunlamp exposed screens.

Measurements of the light output of a number of old fluoroscopic screens have been taken. The results of these measurements, together with the readings taken on some new screens, are shown in table 3. The values shown for a and b represent the average for the initial readings obtained for the 12 group I and 12 group II screens at the start of the screen deterioration study. Screens c and d, both Patterson B-2 screens, were the only old screens tested for which a reasonable age and history of use could be established. Screen c was installed as part of a diagnostic table unit. It had not been used for a number of years. When not in use, the screen had been covered by a black cloth bag. Screen d was purchased new at the same time as c. It was installed on a vertical fluoroscope that had never been used. The entire unit had been stored in a small windowless closet.

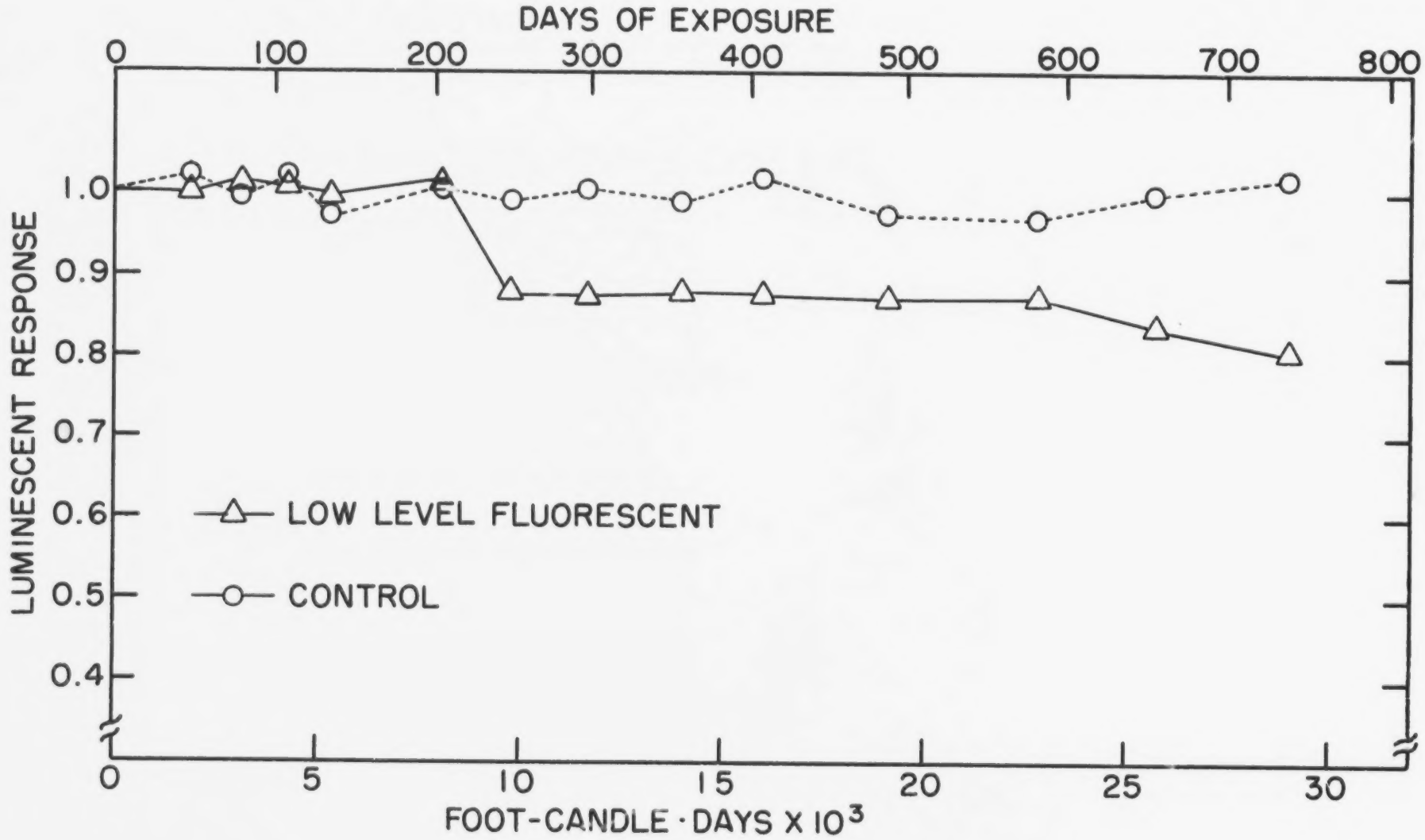

Figure 13A. Relative luminescent response of screens exposed to light from fluorescent lamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure

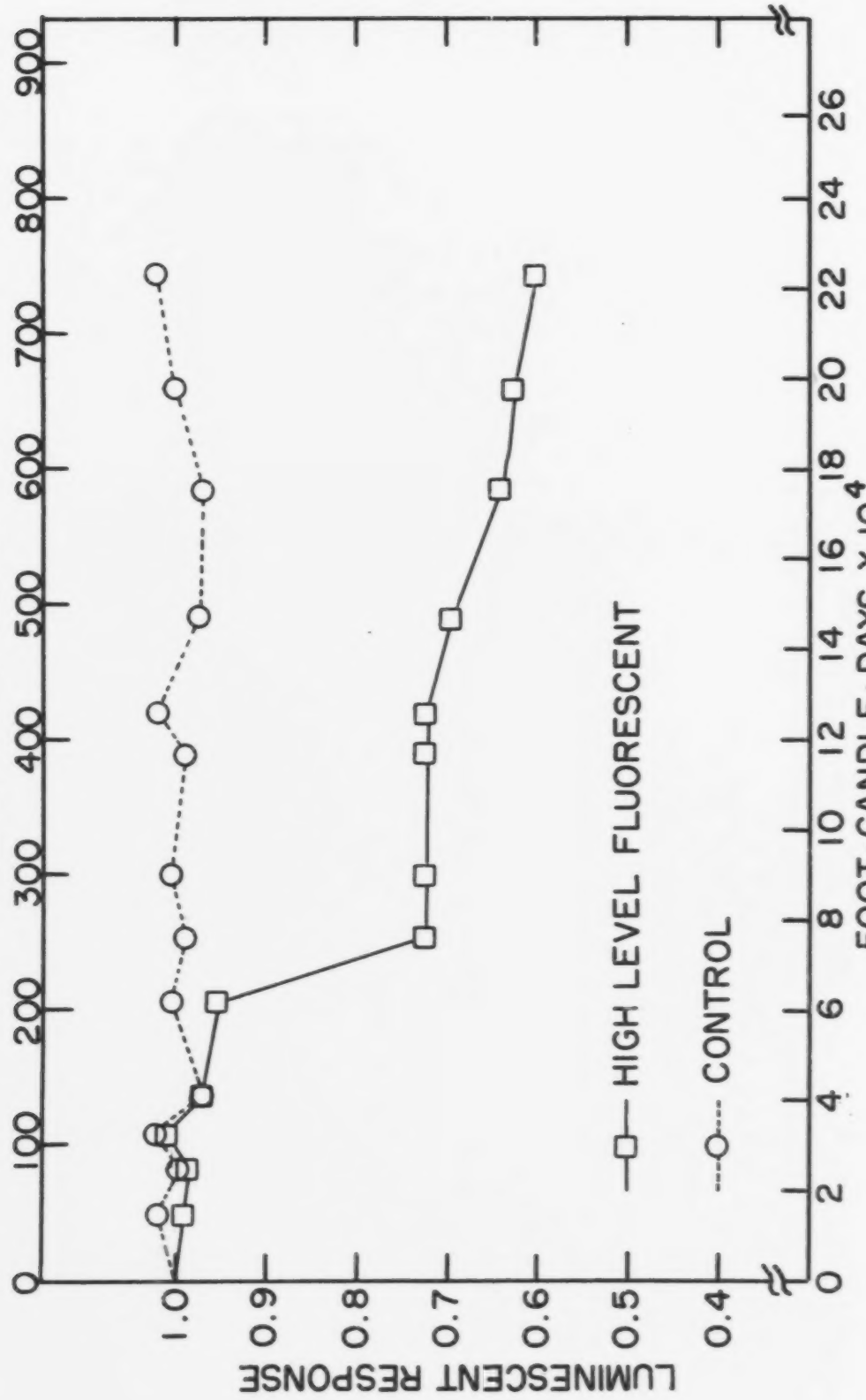

Figure 13B. Relative luminescent response of screens exposed to light from fluorescent lamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure

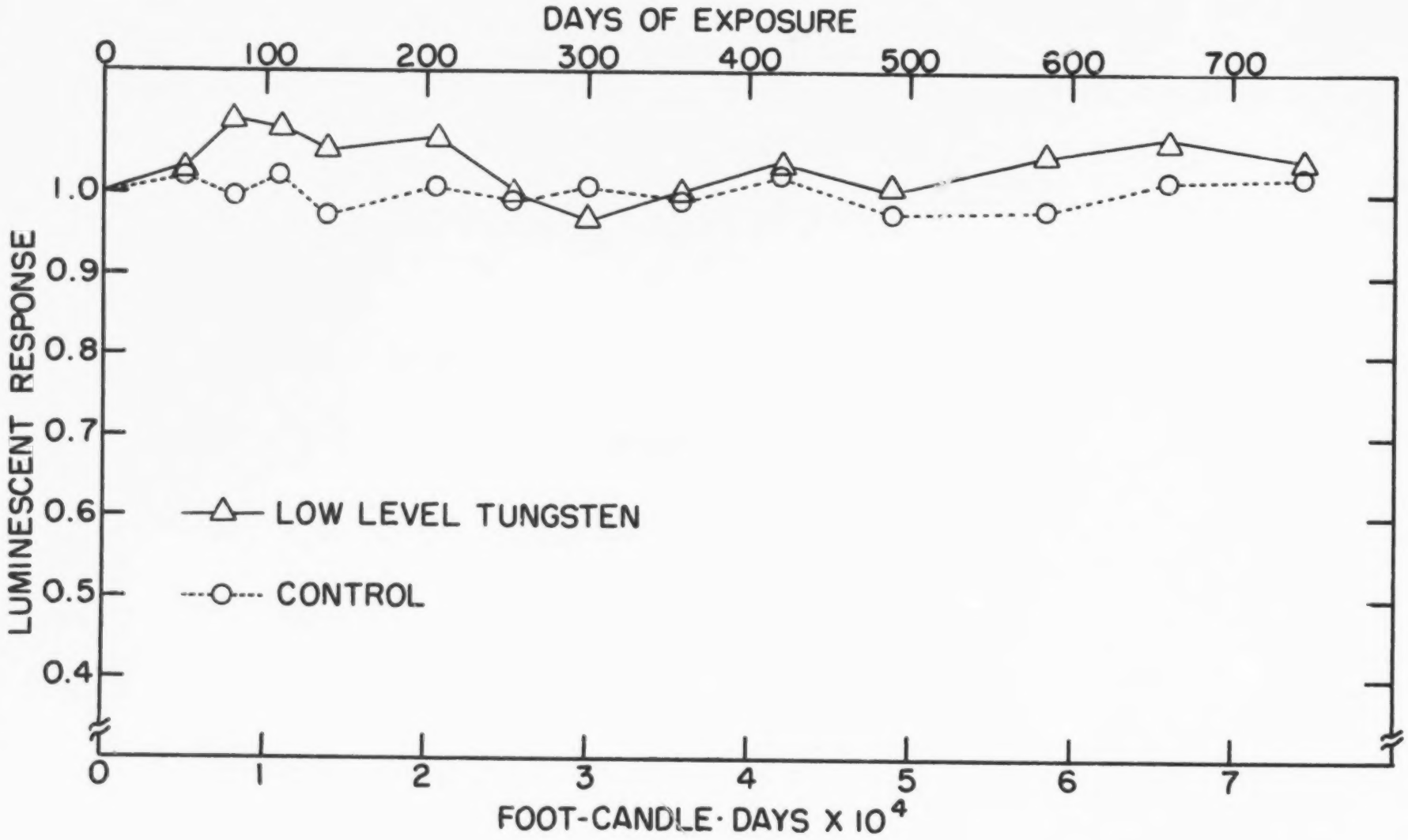

Figure 14A. Relative luminescent response of screens exposed to light from tungsten lamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure

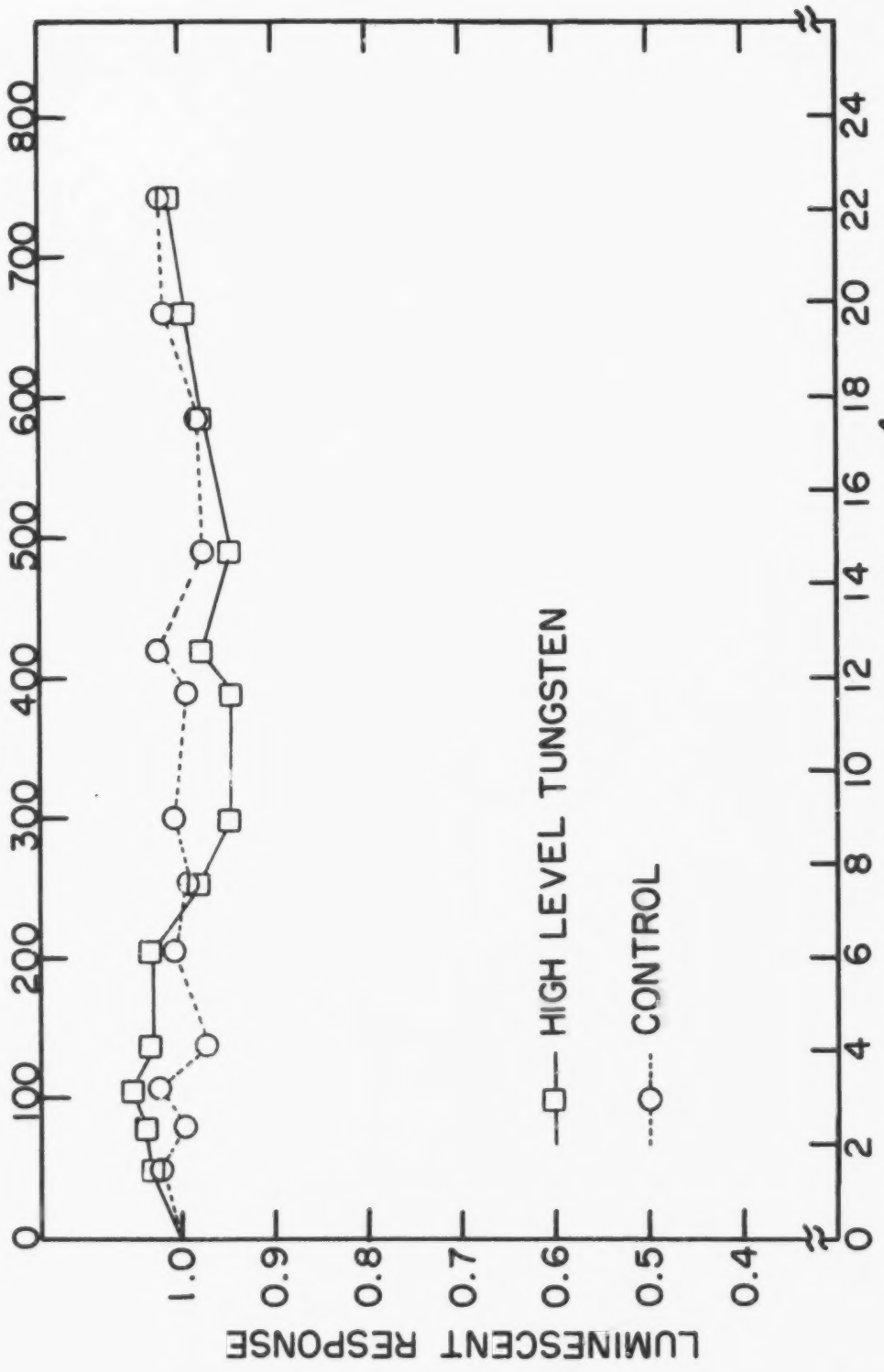

Figure 14B. Relative luminescent response of screens exposed to light from tungsten lamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure

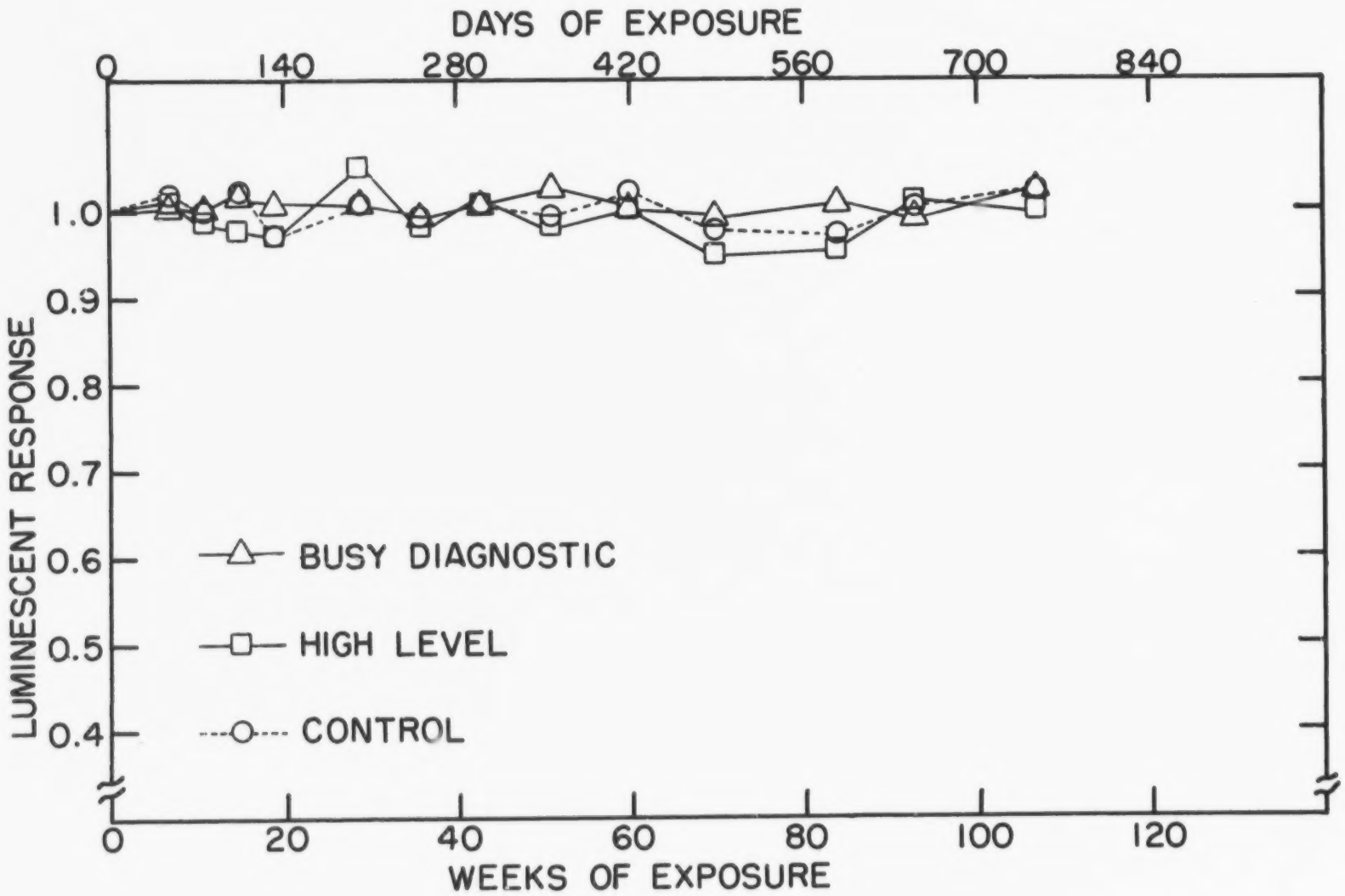

Figure 15. Relative luminescent response of screens exposed to X-rays, excited by 0.5 R/min. at 100 kVp versus the number of weeks or days of exposure

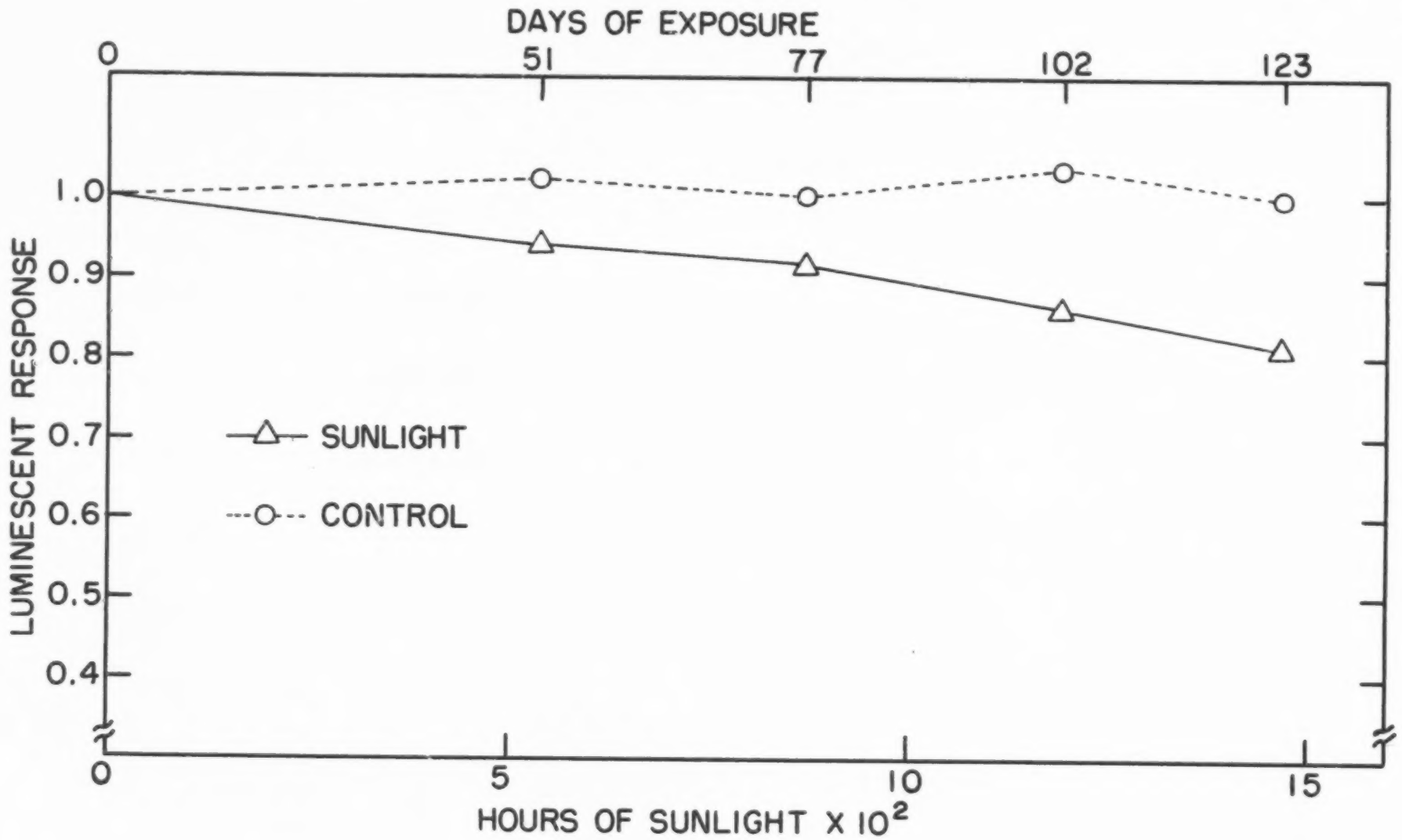

Figure 16A. Relative luminescent response of screens exposed to sunlight, excited by 0.5 R/min. at 100 kVp versus the number of hours of sunlight or days of exposure

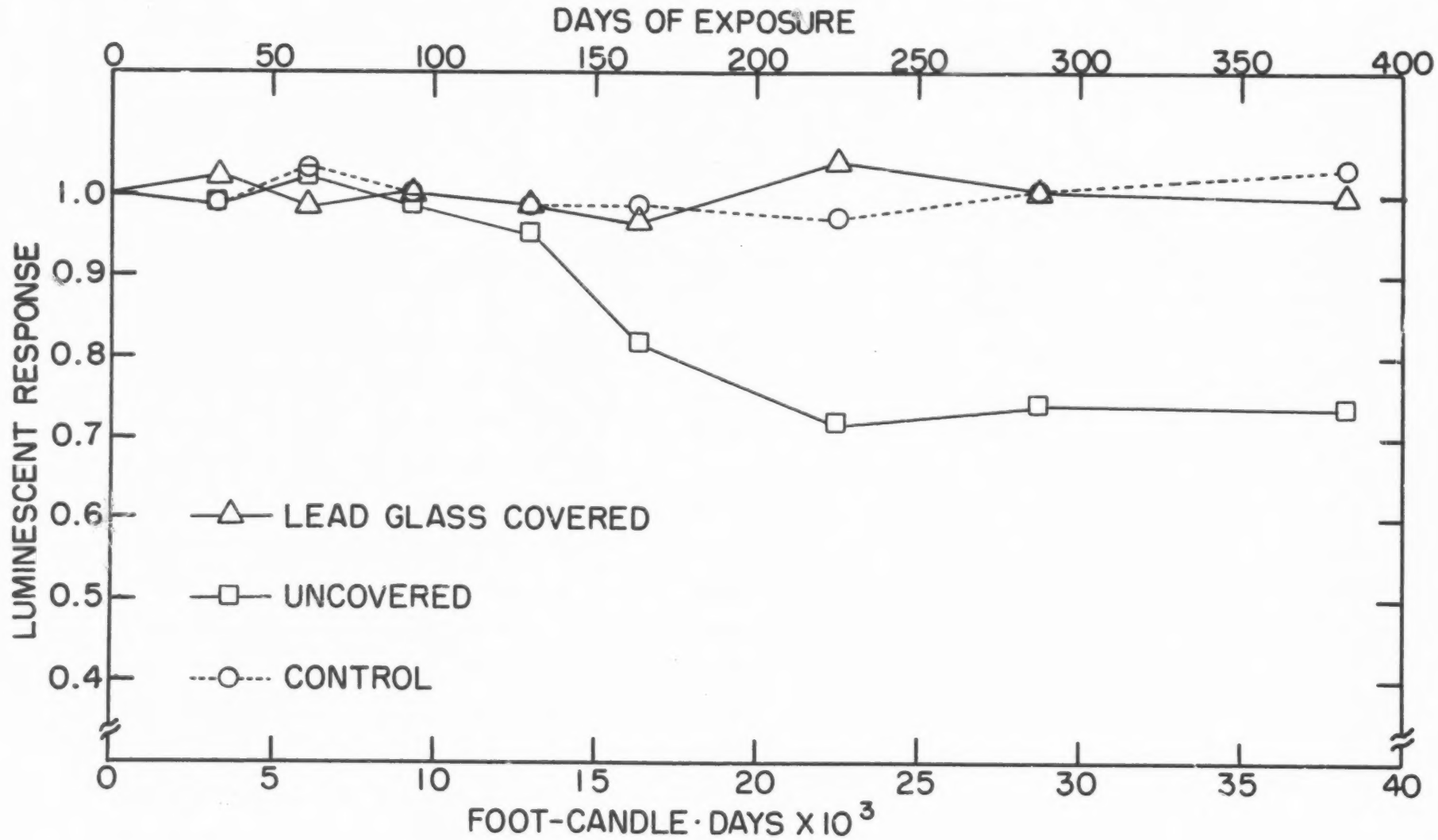

Figure 16B. Relative luminescent response of screens exposed to light from sunlamps, excited by 0.5 R/min. at 100 kVp versus foot-candle·days or days of exposure

Table 3. Luminescent response of a number of new and old fluoroscopic screens

Screen	Luminescence in foot-lamberts, measured at 100 kVp 5 mA (1.29 R/min)	Luminescence in foot-lamberts, measured at 70 kVp 5 mA (0.46 R/min)	Increased exposure factor*
a. Average of 12 Group I	0.075	0.029	1.0**
b. Average of 12 Group II	0.087	0.031	
c. Patterson B-2 (20 years old)	0.074	0.027	1.1
d. Patterson B-2 (20 years old)	0.067	0.026	1.2
e. Patterson B-2 (>14 years old)	0.072	0.028	1.1
f. Patterson B-2 (>14 years old)	0.067	0.026	1.2
g. Patterson B-2 (>14 years old)	0.071	0.027	1.1
h. Patterson B (>20 years old)	0.041	0.017	2.0
i. Patterson B (>20 years old)	0.033	0.014	2.5
j. Patterson A (>35 years old)	0.0115	0.0036	7
k. Patterson A (>35 years old)	0.009	0.0030	9
l. Buck fluoroscopic (>40 years old)	0.0084	0.0028	10

*Factor by which exposure must be increased to obtain the same light output level as the average for a new screen.

**Average output of 12 Group I and 12 Group II screens used as basis for comparison.

IX. SUMMARY AND CONCLUSIONS

Measurements made on old fluoroscopic screens show that over the years there has been an improvement in the luminescent response due to the availability of new types of phosphors and technological advances in the manufacture of fluoroscopic screens. Looking at the information in table 3, the following can be seen:

1. All the old Patterson B-2 screens, two of which were 20 years old and whose history of exposure was known, fall into a narrow group that would require an increase in the exposure rate by a factor of 1.1 to 1.2 to achieve a light output equal to the value for a modern screen. Whether this slight decrease in luminescent response is due to deterioration of the phosphor or to improvements in the methods of manufacture is not known, but certainly there is no marked deterioration. This fact is illustrated by the readings taken on the one 20 year old screen mounted on a vertical fluoroscope. This screen had been protected from the light and never used, but its response did not differ from the other B-2 screens tested by any greater degree than the new screens differed one from another.

2. The Patterson B screens, all more than 20 years old, showed a lower light output that would require an increase in the exposure rate by a factor of 2.0 to 2.5 times that required of a new screen to achieve the same luminescent level.

3. The Patterson A screens, which are at least 35 years old, require an exposure rate about eight times that of a new screen and for the 40 year old Buck Fluoroscopic screen, the exposure rate has to be increased by a factor of ten.

As a result, it can be seen that over a forty-year period it has been possible to decrease the exposure to the patient by a factor of eight to ten times.

Our study was designed to run over a long period of time, and it must be kept in mind that this is a preliminary report. The data presented in this report represents the first 25 months. This excludes the sunlamp exposure group which extends over a period of 13 months.

The two major U. S. manufacturers of fluoroscopic screens state that exposure to ultraviolet radiation will discolor the screens and result in a reduction in their efficiency. Because of this, they recommend that exposure to light be kept to a minimum. It is unclear if this recommendation refers to an unmounted screen or to one covered by a sheet of lead glass. Lead glass is an effective filter for a major portion of the ultraviolet spectrum, so it would be expected that the effect of light on an unmounted screen would be different than the effect on a screen covered by lead glass. To investigate this difference four of the screens in the sunlamp group were

exposed directly to the light and four were exposed through lead glass covers. At the end of 13 months there has been a marked reduction in luminescent response in the uncovered screens whereas there is no change, to date, in the lead glass covered screens exposed to the same level of light. Screens in the other light exposure groups were all exposed through lead glass. This condition realistically tests the effect on a screen mounted on a diagnostic X-ray unit which would normally be covered by a lead-glass barrier. Many of our tests are carried out under conditions that would accelerate any possible deterioration. The screens exposed to sunlight, higher than normal levels of light from fluorescent and tungsten lamps and the high level X-ray exposures are conditions in excess of a normal situation. As an example, it will be noted that at the end of 25 months there is a reduction of about 40% in luminescent response in those screens exposed to very high levels of light from fluorescent lamps whereas those exposed to normal levels exhibit a reduction of about 20%. Following the last point shown for the screens exposed to sunlight, damage resulted due to moisture that drastically reduced their efficiency. The new set of screens obtained to replace the damaged ones are being exposed to light from a sunlamp.

To date lead glass covered screens exposed to tungsten lamps, sunlamps, and X-rays (both the busy diagnostic and high radiation exposure groups) have shown no deterioration. As noted above, we have observed reduced light output from screens exposed to fluorescent lights. First evidence of deterioration appeared on the same number of days, 250, for screens exposed to both low and high level fluorescent light. This indicates the advisability of shielding screen assemblies from fluorescent lamps, a recommendation of both the screen manufacturers.

It should be noted, of course, that the screens under test are being exposed to fluorescent light 24 hours a day; hence the deterioration has appeared in a shorter period of time than would be expected under normal conditions where lights would probably not be on continuously.

It can be said that all fluoroscopic screens more than 20 years old should be replaced with screens incorporating the new phosphors and technological advances. It seems reasonable to believe that some very old screens may still be in use because the 40 year old screen reported on in our study had been in use until it came to us on an obsolete vertical fluoroscope shortly after our study was started.

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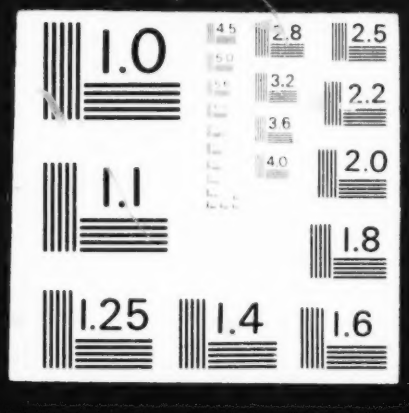

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